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TECHNICAL REPORT ARCCD-TR-88003

SHEAR FORM FABRICATION OF LINERS FOR HEAT PROJECTILES

ROBERT A. ROSSI

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US ARMY
ARMAMENT MUNITIONS
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In an effort to optimize the shear form fabrication process, six groups of shaped charge liners were manufactured. Each group contained a single change in the shear form process. The changes included different starting material, apex shape, and anneal cycle. The penetration performance of the six groups of liners were evaluated by static tests, triple flash radiograph tests, and metallurgical analysis. The evaluation was then used as the basis for the establishment of a process which optimized costs and performance. A quantity of these optimized liners were fabricated and tested as before to characterize penetration performance and metallurgical characteristics. This report and the contractor's Description of Manufacture (DOM) report have been prepared to outline this optimum process which was developed to economically produce a complex shaped charge copper liner for use in HEAT projectiles fired from tank cannons.

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INTRODUCTION

The objective of this project was to optimize the shear form fabrication process for the manufacture of shaped charge liners. The need for this project was the direct result of the development of the XM815 projectile (fig. 1) which was to replace the M456A2 HEAT projectile (fig. 2). During the development of the XM815 warhead, various liner designs were investigated in an attempt to increase penetration performance. These designs used varying wall thicknesses with either a double-angle or complex-curve design. M456A2 liners were a straight constant wall thickness design (fig. 3) and were being manufactured by a mechanically controlled method of shear forming which even at the time was considered to be antiquated. The contractor experienced persistent problems in achieving the required minimum penetration performance. At the time that the XM815 projectile was being developed, the Army went to a new liner producer who proposed to make the M456A2 liners on a computer numerical control (CNC) shear forming machine. The process change was an immediate success. Furthermore, the CNC process appeared adaptable to the more complex liner designs which were required for the XM815. However, the new process needed to be optimized in terms of production costs and penetration.

BACKGROUND

The preliminary liner design chosen for the XM815 was a tulip configuration designed by Physics International (PI) under a contract with Avco. During preliminary evaluations, this design was chosen after considering four candidate liners: a basic 40-degree cone, a biconic design, a tulip design, and a trumpet design. Later, determinations by PI concluded that the tulip liner was too thin in the apex area such that the liner would fail under the setback loads imposed during firing. An increased nose wall thickness would solve the problem; however, the added mass reduced the jet tip velocity. The trumpet design was chosen rather than the tulip design because of greater flexibility, ease of design, small apex angle, structurally sound apex wall, larger head height, lighter weight, and increased explosive charge weight.

New trumpet liners were then designed by PI for the XM815. Static tests were conducted to evaluate the candidate trumpet liners. Four configurations of trumpet liners and a tulip liner for reference were tested. These devices as well as future items were loaded with melt poured 70/30 octol explosive to simulate press loaded LX14 which was planned for the XM815. All liners were fired into rolled homogenous armor (RHA) at built-in standoff. The design which had the deepest penetration then went through several design iterations before the final trumpet design evolved identified as the "B3" design.

A subsequent XM815 test was conducted at Milan Army Ammunition Plant (MAAP) of nine different liner configurations. All tests were conducted against RHA at built-in standoff with spin rates varying from 0 to 30 rotations per second (rps). The B3 liners machined from crossgrain forged bar performed the best followed closely by shear formed B3 and cold-forged tulip liners. Avco concluded that the shear form fabrication process was not yet fully optimized for the B3 design and even further improvements could be realized.

This project was then initiated to define methods for optimizing the B3 liner fabrication process. The program was approved and funded in FY 82. The original plan called for the investigation of two processes for making precision liners: the shear forming process and the Swiss Altdorf cold-forge process. The intent was to compare the performance of liners produced by these two candidate processes and to select one for optimization and detailed evaluation. In the first year, M456 and XM815 liners were to be fabricated by the Swiss cold-forge process. These liners would then be tested in-house ballistically to measure their penetration performance and metallurgically, to determine their material characteristics. In the second year, the XM815 liners were to be fabricated using CNC shear form equipment. Also, M456 shear formed liners were to be obtained from current production. Both of these were to be tested in-house ballistically and metallurgically as previously done for the cold-forged liners. Based on this testing, a choice was to be made as to which process to continue in the third year of this project. The selected process was to be optimized to increase performance and improve the method of production. A quantity of XM815 liners would then be fabricated by this optimized method and these would be tested in-house, as before, to characterize penetration performance and metallurgical properties obtained from this optimized process. The funding for the three years was to be as follows:

FY 82	$ 525,000
FY 83	447,000
FY 84	675,000
Total	$1,647,000

In order to procure the cold-forged liners, a solicitation was issued to PI. The contract was to be a sole source contract because of their licensing agreement with the Swiss government. This license became a major obstacle to a contract because of licensing and royalty fees. After agreements were unable to be reached on costs and level of efforts, it was recommended to investigate only shear forming. In March 1983, Production Base Modernization (PBM) terminated the negotiations with PI and made the project part of the XM815 Avco Systems Contract. This was done to keep both the technology and design work together under one program. During negotiations with Avco in March 1984, the XM815 HEAT program ran into technical difficulties and before a contract was signed, the Avco systems contract for the XM815 was terminated. The project then became an in-house program at ARDEC and was redirected to support the

M456A2, the M830, and the XM859 programs. There were a number of advantages to bringing the program in-house, mainly in that it allowed the advancement of in-house expertise in the area of shear forming. This knowledge could be applied to existing liner production contracts as well as follow-on liner procurements. In addition, the in-house program gave the government greater control over the entire program and the ability to follow the program's progress first hand without having to wait for contractor progress reports.

DISCUSSION

Shear Form Process Description

This work concentrated on the automated shear form, sometimes called flow form, process for the manufacture of precision shaped charge liners. The shear form process (fig. 4) has the advantage of providing built-in spin compensation which proves effective with projectiles such as tank ammunition that have spin. During shear forming, the grain structure of the liner sidewall is twisted about its axis in an opposite direction to the projectiles rotation during flight. This results in an ideally axial jet with maximum penetration effectiveness.

The shear form process appears to be similar to the spinning process; however, the two processes are quite different (fig. 5). In spinning, the starting blank is formed over a mandrel with little or no reduction in wall thickness. In shear forming, the metal flows over the mandrel entirely by shear. The finished part has a much thinner wall thickness than the starting blank. This reduction is thickness is caused because the gap between the roller and the mandrel is less than the thickness of the starting blank. The rollers virtually stretch the copper along the mandrel and the blank increases to the required length.

Prior M456 liner production used vertical two-roller Lodge and Shipley Flo-turn equipment (figs. 6 and 7). The contour of the liner was controlled mechanically using a system of hydraulically operated cams and the temperature was maintained by a heated mandrel. To maintain dimensional control and to keep the final temperature of the liner at a constant preselected temperature, the operator made continual adjustments to the coolant mist and the roller alignment. In recent times, this equipment was considered to be antiquated as the contractor experienced many production problems in passing acceptance test requirements. The main problems was that the process could not be controlled with any degree of consistency, and the result was a borderline product that often had less then required minimum penetration. The continual operator-controlled coolant and roller adjustments required by the process made repeatability difficult.

With advances in technology, the shear form equipment has been interfaced with computer numerical control (CNC) systems and the result is a reproducible product having consistent penetration performance. The liners for this project were manufactured by Envirotronics Inc. They were made on an Autospin shear form machine which was assembled in modular fashion using a combination of standard and oversized components to increase rigidity and accuracy. Accuracy was also enhanced by using linear, electro-hydraulic pulse drives capable of 0.0005-inch resolution.

A list of operations which make up the production process used for this project are included in table 1. The starting blank is preformed from the starting material into a round disc, 4.25-inch diameter and 0.4-inch thick. A dimple is added to the center of the disc to locate the disc between the mandrel and the tailstock ram. The shape of the mandrel (fig. 8) determines the inside configuration of the liner. The tailstock follower (fig. 9) clamps the starting blank against the tip of the mandrel and keeps it in position while controlling part slippage. During the shear forming operation (fig. 10) a single forming roller displaces the spinning blank over the spinning mandrel and controls the final part contour. The roller passes from the tailstock end and travels towards the headstock while forcing the copper to flow in the same direction. The starting blank is put on the machine at ambient temperature and flooded with coolant during the single pass operation so that the liner remains at approximately ambient temperature. After shear forming, a 75-ton press is then used to form the rounded apex and to coin and trim the flange to shape. Following a degreasing operation, the heavily cold worked liners are annealed in a continuous belt-type oven to achieve a recrystallized, fine grain structure in the 15- to 20-micron range. Following the anneal, the liners are quenched in a room temperature water bath and measured on the outside surface of the body for Rockwell F scale hardness. The nose and flange are then machined to final shape and the liners are washed, final inspected, and packaged.

Description of Liner Groups A through F

Six groups of liners were manufactured by Envirotronics with one process variable changed in each group. A seventh optimum group, G, will be discussed later.

Certain process variables were kept constant throughout the work and were not challenged as being optimal parameters. These baseline parameters include the use of the trumpet-shaped liner, CNC shear forming equipment, the use of a post-forming anneal to obtain a final grain size of 15 to 20 microns, and the use of octol explosive. These base parameters were defined by previous related work which had identified them as the latest technology in the liner design and processing areas.

The number of parts manufactured by group and end use are as follows:

Item	Quantity						
	Group						
	A	B	C	D	E	F	G
Starting blank (metallurgy)	2	2	2	-	2	-	-
Before anneal (metallurgy)	4	4	4	4	4	4	4
After anneal (metallurgy)	4	4	4	4	4	4	4
Historical samples	13	5	5	5	5	5	5
Loading samples (practice loading)	5	-	-	5	-	-	-
Static test (testing)	25	25	25	25	25	25	25
Triple flash radiographs (testing)	4	2	2	2	2	2	4

The six groups of liners, all annealed, are described as follows:

Group A, Baseline: This is the final B3 liner design (fig. 11) developed during the XM815 program. It established a baseline with which to compare other iterations. The starting material is C102 oxygen free copper strip, 0.4-inch thick.

Group B, Forged Bar Blank: The starting blank material is C102 oxygen free copper bar which has been cold forged to 0.35-inch blank thickness. This was an attempt to reduce material waste by using a thinner blank. It was also an attempt at increased performance due to a larger amount of cold work and changed grain orientation.

Group C, C120 Copper: This material change from C102 copper strip to C120 copper strip was an effort to lower material costs by using a more available commercial grade of copper. The blank was 0.4 inch thick.

Group D, As-Formed Apex: By eliminating the press backward extrusion operation which provided the rounded apex, the result was a "flat top" liner configuration. This offers cost savings due to reduced press, machining, gaging, and scrapped parts costs. The material was C102 copper strip.

Group E, Forged Strip: The starting blank material was C102 copper strip as in the baseline group A; however, the strip is cold forged to a final blank thickness of 0.35 inch. This group was an effort to economize by using a thinner starting blank. It was also an attempt at improved penetration performance due to the induced cold work resulting from the forging process.

Group F, Higher Hardness: By using a shorter anneal cycle, production time could be reduced. Also, the effect on penetration performance of increasing the hardness of the liner was studied. The material was C102 copper strip.

Liner Design Configuration

When the XM815 systems contract was terminated with Avco, the final B3 design was carried over into the ARDEC in-house program. The Avco B3 liner drawing depicted the contour of the liner by polynomial equations, one equation for the interior contour and one for the outside contour. All dimensions were metric. In converting the Avco drawing for use on this project, the polynomial equations were converted to X and Y coordinates. Selected coordinates were then used to generate radii which would develop both the outside and inside wall contours (fig. 11) The inside contour was defined with basic datum diameters and toleranced linear dimensions. The outside contour was defined by toleranced diameters and basic linear dimensions. With the elimination of the polynomial equations, a more conventional means of inspection became possible

Manufacture of Liner Groups A through F

Operation 1–Material Requisition (all groups)

Copper alloy, oxygen free, ASTM B152, hydrogen embrittlement not permitted

Groups A, D, E, and F - 102 copper alloy rolled strips, 0.4-inch thick
Group B - 102 copper alloy bar stock, 2.5-inch diameter
Group C - 120 copper alloy rolled strip, 0.4-inch thick

Operation 2–Cut Bar (group B only)

Cut to 1.025-inches long and deburr

Operation 3--Forge Blanks (groups B and E only)

Forge flat to 0.350-inch thick, 4.25-inch minimum diameter

Operation 4--Form Blanks (all groups)

Blank and dimple tc preform shape (figs. 12 and 13)

Operation 5--Anneal Blanks (group B only)

The high degree of cold working which took place in operation 3 required an anneal to lower the hardness to an acceptable level for shear forming.

Operation 6--Shear Forming (all groups)

Shear form at 1400 rps on an Autospin model AS-1230-CNC. The mandrel is spun in a counterclockwise direction with respect to the roller slide. The single-pass process time is approximately 40 seconds at a constant forming rate of 0.1 inch per second. The blanks are initially at room temperature and are flooded with coolant so that the finished part is approximately 90°F.

Operation 7--Machine Apex (groups B and E)

Machine the apex in preparation for the backward extrusion. This operation is only groups B and E due to their greater hardness.

Operation 8--Machine Apex (group D)

Final machine the apex for the as-formed liner (fig. 14)

Operation 9--Coin Operation (all groups)

Using a Bliss 75-ton mechanical press, coin the flange. The coining establishes the location of the flange. It thins the flange while making the flange outside diameter larger.

Operation 10--Trim Operation (all groups)

Using a Bliss 75-ton mechanical press, trim the flange. This removes excessive stock and results in a more efficient final machining operation.

Operation 11--Apex Extrusion (groups A, B, C, E, and F)

Using a Bliss 75-ton mechanical press, backward extrude the apex. Material is caused to flow into the cavity of the die.

Operation 12--Degrease (all groups)

Prior to anneal, degrease in order to insure that there are no contaminants.

Operation 13--Anneal (all groups)

Use a 2000°F Inconel belt conveyor type furnace. The oven is heated by approximately 60 electric coils along its 16-foot length. The internal atmosphere of the oven is kept neutral by injecting a curtain of nitrogen gas at the front and rear openings of the furnace. The conveyor speed was adjusted to achieve the required Rockwell F scale hardness objective. The oven temperatures for each of the six groups are listed below:

Group A	875 to 930°F
Group B	no record
Group C	975°F
Group D	900°F
Group E	855°F
Group F	750°F

Operation 14--Quench (all groups)

Immediately, upon exit from the furnace, quench in a room temperature circulating water bath.

Operation 15--Hardness check (all groups)

Pull samples from each quench basket and perform a Rockwell F scale hardness check on the outside body of the liner about 1.5 inches above the flange. The hardness objective was:

Groups A through E	40 to 54
Group F	55 to 60

Operation 16--Machine Apex (groups A, B, C, E, and F) **and Flange** (all groups)

Final machine the apex and flange in accordance with the drawing (fig. 11) on a Moriseiki Model MS-850 lathe.

Operation 17--Final Inspection (all groups)

Final inspect; also inspect the outside contour on a 30-inch comparator.

Operation 18--Pack

Pack according to MIL-STD-1169

Operation 19--Ship

75/25 Octol Explosive Loading of Test Items

The 164 rounds from groups A to F and the final 29 rounds from group G were loaded on Milan AAP's X-41 line which is normally used for comp B melt pour production loading of M456 projectiles. The groups of liners were evaluated by using 75/25 octol loaded 105 mm M456 HEAT-T projectiles as test vehicles. Octol explosive was chosen as an extension of previous XM815 development testing. It is a more energetic explosive than comp B which is used in the M456A2.

After numerous attempts, MAAP was unable to load the octol explosive successfully. The problem revealed by radiography was excessive cavitation and cracks in almost 100% of the rounds. Because a local solution seemed unlikely, assistance was requested from the Energetic Systems Process Division at ARDEC. A loading test plant was prepared based on their previous experience with octol explosive. The results of applying that new test plan were highly successful. X-ray analysis of the projectiles loaded revealed 99% acceptance (161 acceptable versus two rejects). Details of the octol loading procedure are included in the appendix.

A sample of nine practice loading rounds were subsequently shipped to ARDEC for chemical composition analysis and density determinations of the octol load. The results of this analysis are also included in the appendix.

Before explosive loading, the metal-parts assemblies werre measured for liner runout and dry weight. Liner runout is a measure of the concentricity of the liner with the initiating charge and projectile body. The runout requirement for the M456A2 is 0.015 inch maximum. The rounds were again weighed after octol loading and the explosive weight was computed. The results of the runout and explosive weight are summarized as follows:

Group	A	B	C	D	E	F
Average runout (in.)	0.006	0.004	0.005	0.007	0.005	0.004
Average explosive weight (lb)	2.49	2.50	2.46	2.48	2.49	2.49

Static Penetration Evaluation

Test Description

Groups A through F were tested at Milan AAP using the same static test equipment normally used to test M456A2 liners for production acceptance. The test stand is an above ground steel structure (fig. 15). The target material was mild steel stacked so that the first three blocks were each 5-inches thick and the remaining blocks were each 3-inches thick. The test warhead was assembled with an M456 spike on the front of the body and a modified boom assembled on the rear (fig. 16). A wire connected the round to the test stand motor, which was used to impart the required spin. The maximum standoff distance from the tip of the spike to the target stack was 0.250 inch, so that the tests were performed at essentially built-in standoff.

The first six groups (A through F, 149 rounds) were tested in a 1-month period. Each group of 25 liners was tested at selected spin rates ranging from 0 to 40 rotations per second (rps). Recorded data included spin rate, entrance hole diameter, exit hole diameter, and penetration depth. Also, four samples were fired into rolled homogenous armor plate (RHA).

Test Results

Static penetration data from testing groups A thorugh F were curve matched using second order polynomial equations and the results are shown in figures 17 through 23. In the 0 to 20 rps range, the average penetration of all six groups was approximately +5.0 inches and varied by only 1 inch. In this spin range, group D liners with the as-formed apex performed slightly better than the others and reached a maximum of nearly +6.0 inches at 15 rps. At spin rates higher than 20 rps, the performance curves of the several groups began to diverge. The group F liners with a higher hardness were able to hold their performance the best with +4.0 inches at 40 rps. The baseline group A showed the largest deterioration in performance at high spin rates with a +1.5-inch average.

For reference: The TOW missile fires at 0 rps, 105 mm M456A2 HEAT spins at approximately 15 rps, and the 120 mm M830 HEAT spins at approximately 30 rps.

A noteworthy characteristic of the results is the relatively flat profile of the penetration versus spin rate curve. In earlier shearform liner production from early 1960 through 1983, there was an obvious peak in the penetration at between 10 to 20 rps while at 0 to 10 rps and 20 to 30 rps the results were considerably lower. The flatter curve achieved in this testing was believed to be due to the method developed by this manufacturer of annealing the liners after shear forming. This was not done in prior production.

Note: Test results are presented as + or – with respect to 17 inch minimum required penetration of the M456A2. Penetration results were declassified in accordance with Memorandum for AMSTA-AR-PSI signed by Colonel Gary Payne Dated 30 April 1999.

This note goes on page 10 of the report

Selection of Group G Parameters

The selection of process parameters used in the manufacture of the group G liners was based on the static test results of groups A through F while taking into account performance and possible cost savings. On this basis, it was decided to combine the characteristics of groups C, the C120 copper; group D, the as-formed apex; and group F, the higher hardness.

Group C was chosen because of the cost savings and material availability advantages to be gained by using the more inexpensive and widely available C120 copper alloy. This alloy is approximately 14 cents a pound or 28 cents a liner cheaper than C102 copper.

Group D liners with the as-formed apex showed improved performance in comparison to the baseline group A which had the more widely accepted and used rounded apex design. Besides the advantage of enhanced penetration, manufacturing costs are reduced by approximately 25 cents a liner because of the elimination of a press operation, reduced gaging costs, and a lower scrap rate.

Group F liners with increased hardness showed the best ability to resist deterioration of penetration performance at high spin rates. At all spin rates above 20 rps, group F liners were apparently superior and have a lower annealing temperature which results in a higher hardness.

Manufacture of Group G

Group G liners were manufactured by Envirotronics approximately 4 months after the static testing was completed on groups A through F. All manufacturing parameters were kept the same as for the manufacture of the first six groups with the exception of the use of C120 copper, the as-formed apex, and the higher hardness. The contractor estimated that the parameters chosen for the manufacture of group G would provide a 5 to 10% reduction in the end-item cost. During the anneal cycle, a decision had to be made as to what temperature to use for group G since group C (C120 copper) had been annealed at 975°F and group F (higher hardness) was annealed at 750°F. Based on its previous use as the anneal temperature for the group C liners, it was decided to use 975°F and to adjust the time of anneal to provide the higher hardness and required grain size.

A description of group G fabrication process follows:

Operation 1--Material Requisition

Copper alloy, oxygen free, ASTM B152, hydrogen embrittlement not permitted, 0.4-inch thick, 120 copper alloy rolled strip

Operation 2--Form Blanks

Blank and dimple to a preform shape (fig. 12)

Operation 3--Shear Forming

Shear form at 1400 rps on an Autospin model AS-1230-CNC. The mandrel is spun in a counterclockwise direction with respect to the roller slide. The single pass process time is approximately 40 seconds at a forming rate of 0.1 inch per second. The blanks are initially at room temperature and are flooded with coolant so that the finished part is approximately 90°F.

Operation 4--Machine Apex

Final machine the apex for the as-formed liner (fig. 14)

Operation 5--Coin Operation

Using a Bliss 75-ton mechanical press, coin the flange. The coining establishes the location of the flange. It thins the flange while making the outside diameter larger.

Operation 6--Trim Operation

Using a Bliss 75-ton mechanical press, trim the flange. This removes excessive stock and gives a more efficient final machining operations.

Operation 7--Degrease

Prior to anneal, degrease in order to insure that there are no contaminants.

Operation 8--Anneal

Anneal at 975°F in a belt conveyor furnace.

Operation 9--Quench

Upon exit from the furnace, immediately quench in a room temperature circulating water bath.

Operation 10--Hardness Check

Pull samples from each quench basket and perform a Rockwell F scale hardness check on the body of the liner. The hardness objective was RF 55-60.

Operation 11--Machine Flange

Final machine the flange in accordance with the drawing (fig. 11) on a Moriseiki model MS-850 lathe.

Operation 12--Final Inspection

Final inspect, also inspect the outside contour on a 30-inch comparator.

Operation 13--Pack

Pack according to MIL-STD-1169

Operation 14--Ship

Static Penetration Evaluation of Group G

Group G liners were also loaded and tested at MAAP using identical facilities and test procedures as done previously for groups A through F. Twenty five group G liners were tested at various spin rates ranging from 0 to 40 rps. Two of these samples were fired into RHA.

The results of the static penetration testing of group G are shown in figures 24 and 25. In the 5 to 20 rps range, the optimum range for the M456A2, group G liners had marginally better performance than all other groups and reached a maximum of over +6.0 inches at 10 to 15 rps. The hope of increased penetration at higher spin rates was not realized as the performance of group G at high spin did not come up to that achieved by group F liners.

Statistical Analysis of Penetration Data

A statistical analysis was performed to determine any differentiation or degradation in penetration performance among the seven different groups of liners.

An analysis of variance (ANOVA) was performed on the test data. It was found that there is a difference in the relation of penetration to spin rate from group to group. However, it was determined that all the groups exhibited equivalent penetration performance.

In addition to ANOVA, a multiple comparison test of means was conducted. From this analysis, it was concluded that there is no statistical evidence that the means of the different groups differ from each other. This test was performed at different spin-rate combinations including 15 and 30, 10, 15, and 20 and at separate spin rates 0, 15, and 30 rotations per second. All tests resulted with the same conclusions, that the groups did not differ.

Triple Flash Radiograph Testing

Triple flash radiography is often used as a tool to diagnose and investigate the performance and characteristics of a shaped charge liner. By using an exposure time in the nanosecond range, it is possible to capture the image of the liner jet on film. Data which can be gathered and calculated include the jet tip velocity, breakup time, kinetic energy, momentum, particle velocity, diameter, length, length-to-diameter ratio, mass, and jet virtual origin. The data are recorded by using intensifier screens to stop the motion of the jet and record the image on film.

The triple flash radiograph testing was done at ARDEC. The test facility is shown in figures 26 and 27. It consists of three Hewlett Packard model 2710, 300 kilovolt pulsers. The three tube heads are equally spaced with a 60-degree angle between them. The radiated area is limited by lead collimators. This causes a focused beam of radiation which does not effect adjacent film strips. The x-ray system is triggered by a pulse obtained when detonation occurs. Each tube is pulsed so that three independently timed radiographs are produced. The warhead is detonated on top of a six-inch thick armor plate and the jet travels downward through a round hole in the plate and passes in front of the film cassettes (figs. 28 and 29). A wooden test stand with an electric motor was built to provide the required rotation (fig. 30). The rotation speed chosen for most rounds was 15 rps, the typical speed of the 105 mm M456A2. Some of the rounds were fired at 0 rps. An aluminum test spin adapter was built and screwed into the rear threads of the warhead body. The adapter contained the booster pellet and an RP-1 initiator. The test-spin adapter and assembled warhead are shown in figure 31.

The x-rays were triggered at 100, 140, and 180 microseconds after the detonation. The warheads were fired into a target stack of RHA steel located at a standoff distance of 20 charge diameters. The target stack consisted of 9-inch squares of 2-inch thick RHA (fig. 32).

Triple Flash Radiograph Test Results

Examples of the triple-flash radiographs for group A are shown in figure 33. In the radiograph at the top of the page, the round A65 was not spinning and on the bottom of the page, round AF14 was spinning at 15 rotations per second (rps) are shown in figures 34 through 39.

A total of 18 triple-flash radiograph tests were performed. The data were collected at ARDEC and analyzed using BRL lab equipment. The results of this computer analysis are included in table 2. Specific observations noted by ARDEC are listed in table 3. General observations are as follows:

a. The jets were all ductile, and aside from a little hollowness in some tip particles, showed no radial dispersion associated with spin.

b. The rounds with as-formed apex (groups D and G) have more bunching of material in the tip, and as a result are slightly slower than the other jets. This is a result of the geometry of the liner apex.

c. There are no obvious differences in velocity or appearance between static firing and the firings at 15 rps.

d. Penetrations appear to be solely a function of jet straightness with the more severely bowed jets providing the lowest penetrations. The bowing seen is generally associated with liner-explosive asymmetries.

Metallurgy Analysis Results

A metallurgical analysis was performed, and the results summarized:

Blank Preform

	A	B	C	D	E	F	G
Copper alloy	102	102	120	102	102	102	120
Grain size (microns)	30	[a]	45	30	35	30	45
Average direct suface hardness, Rf	72	77	76	72	83	72	76
Yield strength (kpsi)[b]	18.4	52.4[c]	17.1	18.4	33.6	18.4	19.3
Ultimate strength (kpsi)[b]	32.5	55.4[c]	32.6	32.5	37.0	32.5	33.1
Percent elongation in 1 inch[b]	53	17[c]	49	53	34	53	48
Reduced area (%)[b]	86	78[c]	87	86	89	86	89

[a]Nonhomogenous grain structure

[b]Contractor supplied lab analysis results

[c]Before blank anneal

Sheets A (102) and C (120) were comparable in hardness and are classified as material between 1/4 and 1/2 hard. In general, the surface hardness was slightly higher than the mid-wall hardness. Sheets B (102) and E (102) were slightly harder than A and C with B approaching a 1/2-hard condition and E equivalent to a 1/2-hard condition. The higher hardness of sheets B and E resulted from the additional forging operation. The annealing treatment of sheet B was judged to be a partial one, producing only a slight hardness reduction. The microstructures of materials A, C, and E were uniform throughout the regions examined, exhibiting a prior recrystallized grain structure. In contrast, the microstructure of sheet B was not uniform. Adjacent regions within the sheet exhibited a fine and a coarse partially recrystallized microstructure. The different microstructures found in this material resulted from the nonuniform forging process and the incomplete annealing treatment.

As-Formed Liner (Before Anneal)

The microstructure and hardness of the as-formed liners were found to be generally uniform with little differences noted within a given liner or from one liner to another. This was not anticipated since the starting blank materials were markedly different in terms of the manner and extent of cold working, especially when comparing starting material A with material B or E. With the exception of the material adjacent to the apex, the hardness was essentially uniform along the liner length. The apex region was slightly harder for all liners which had the extruded tip. These general trends were observed from the microhardness measurements as well as the direct Rockwell F measurments. The microstructure of the as-formed liners was uniform exhibiting a high degree of metal flow aligned parallel to the liner surface (fig. 40).

		A	B	C	D	E	F	G
Direct surface hardness, (RF) location (fig. 41)	1	92	96	96	93	95	94	90
	2	93	95	95	94	93	93	95
	3	95	94	94	92	92	92	93
	4	95	94	92	91	91	91	93

Annealed Liners

The hardness values of the annealed liners in groups A through F were not uniform to the extent observed in the as-formed liners. For example, in liners B, C, and E the hardness of the apex region was significantly higher than that near the flange. Moreover, in liners C and E, the hardness of the midlength regions was higher than anywhere else. The hardness of group G was not as uniform as the hardness exhibited by the other groups. This observation agrees with the microstructure analysis of group G.

The microstructures of the annealed liners were essentially uniform with the exception of group G liners. The grain size was 15 microns in groups A through F (fig. 42). The microstructures of group G liners were nonuniform especially near the apex and flange of the liner. In these areas, the structure was nonuniform with areas of cold work structure still existing. In the midlength areas where the structure was fully recrystallized, the grain size was only 10 microns (fig. 43).

		A	B	C	D	E	F	G
Direct suface hardness (RF) location	1	45	45	60	43	60	49	61
	2	47	45	60	45	59	48	63
	3	48	46	56	44	59	49	67
	4	48	45	50	44	50	48	72

The actual hardness values shown here are not necessarily representative of the hardness values for the entire group since only one liner from each group was randomly chosen for metallurgical examination. According to hardness test data gathered on all liners during manufacture, as intended, group F like group G liners had much higher hardness than other groups. The average hardness for each group of liners ballistically tested is:

	A	B	C	D	E	F	G
Direct surface hardness (RF) (measured on liner body during manufacture)	45.0	41.4	47.2	43.9	44.7	57.0	56.0

CONCLUSIONS

1. The trumpet liners made from blanks and shear formed over a mandrel on a CNC machine and post annealed to a fine grain size resulted in a reproducible product having consistent penetration performance.

2. The performance obtained with these shear formed liners is a relatively flat penetration versus spin curve out to 25 rps.

3. The shear form process parameters which were studied did not show a statistical contribution towards performance.

4. Implementation of the identified shear form process parameters changes: 120 copper alloy instead of 102 copper, the as-formed apex instead of the extruded and machined apex, and the shorter anneal cycle, will result in reduced costs and production time providing an estimated 5 to 10% reduction in the end item cost.

RECOMMENDATIONS

1. Technical data packages for liners which do not presently specify shear forming should be examined with a view to including it as an alternative production process.

2. An area of additional future work might be to investigate the baseline parameters which were kept constant throughout this work. These baseline parameters include the use of the trumpet shaped liner, computer numerically controlled (CNC) shear forming equipment, the use of a post-forming anneal, and the use of octol explosive. For example, an area of further study might be to compare the product resulting from CNC and non-CNC shear forming equipment to determine capabilities in terms of dimensional accuracy and penetration performance. Another area of future work might be to better define the contribution of the post forming anneal on-liner performance. The choice of liner design whether it be trumpet, straight wall, biconic, or tulip should be evaluated in each specific application and operating environment.

3. With regard to the six parameters studied on this project, additional factors such as cost, availability, and ease of processing should determine their selection. Consequently, a conservative approach during development would be to evaluate these parameters as well as liner geometry in each specific application.

Table 1. Shear forming operations, groups A through F

Operation No.	Operation
1	Material requisition
2	Cut bar (B only)
3	Forge blanks (B and E only)
4	Form blanks
5	Anneal blanks (B only)
6	Shear forming
7	Machine apex (B and E only)
8	Machine apex (D only)
9	Coin
10	Trim
11	Apex extrusion (except D)
12	Degrease
13	Anneal
14	Quench
15	Hardness check
16	Machine nose (except D) and flange
17	Final inspection
18	Pack
19	Ship

Table 2. Triple flash radiographic data analysis

Liner	Pen	V_j	V_{j7}	t	Mass	KE	Mom
AF14*	6.50	8.9	7.97	135.8	3.44	127	29.6
A65*	5.25	9.31	8.37	131.3	3.47	139	31.0
AF7	6.37	9.24	8.45	134.4	3.56	144	32.0
B29	9.12	9.07	8.32	116.1	3.53	137	31.1
B44	9.00	8.98	8.17	119.4	4.77	181	41.5
C48	11.00	8.96	8.22	124.2	2.64	99	22.9
C18	6.00	9.10	8.27	134.5	4.22	164	37.2
D36	9.37	8.87	8.07	121.6	3.73	137	31.9
D21	6.00	8.78	8.07	121.6	3.73	137	31.9
E21	13.87	9.00	8.30	117.7	2.49	93	21.5
E9	7.25	8.95	8.28	126.6	2.66	103	23.1
F33	12.50	8.89	8.07	126.7	3.51	128	30.0
F26	6.00	9.02	8.33	129.0	2.72	105	23.9
G18	8.87	8.84	8.13	132.5	4.10	153	35.4
G11	10.00	8.76	7.98	106.4	7.39	277	64.0
G3*	12.00	8.87	8.19	122.5	4.06	154	35.3
G73*	10.00	8.84	8.14	128.1	3.15	116	27.1
Average	8.77	8.96	8.20	125.5	3.66	139	31.9

Note: Pen - Penetration at 20 CDs standoff into RHA (in.)
V_j - Jet tip velocity (mm/μs)
V_{j7} - Jet velocity particle 7 (mm/μs)
t - Jet breakup time (μs)
Mass - Total jet mass of first seven particles (g)
KE - Total kinetic energy of first seven particles (kJ)
Mom - Total momentum of first seven particles (kg m/s)

*Static firing; others fired at 15 rps

Table 3. Specific radiographic observations

Warhead	Specific observations
AF14	Bowed in B and C; hollowness in tip; wispy precursor
A65*	Bowed in A, B, and C; hollowness in tip; wispy precursor
AF7*	Bowed in B and C; precursor folding back; ring in tip
B29	Fairly straight, precursor with ring
B44	Slight bow in C; precursor with ring
C48	Straight; precursor folding back; ring in tip
C18	Bowed in B and C; cohesive precursor with ring
D36	Fairly straight; bunching at tip, folding back; no ring
D21	Bowed in A, B, and C; bunching at tip, folding back; no ring
E21	Straight in C; slight waver in A and B; precursor folding back; ring which expands and breaks
E9	Bowed in A and B; wispy precursor displaced from tip
F33	Slight bow in A and B; precursor which separates; ring in tip; hollowness in tip particles
F26	Bowed in A and C; S shaped in B; precursor folding back; ring in tip; hollowness in tip particles
G18	Bowed in A, B, and C; bunching at tip
G11	Slight bow in A, B, and C; lead particle folding back and falling apart
G3*	Slight bow in A, B, and C; bunching at tip
G73*	Gentle bow in B and C; bunching at tip

*Static firing, others fired at 15 rps

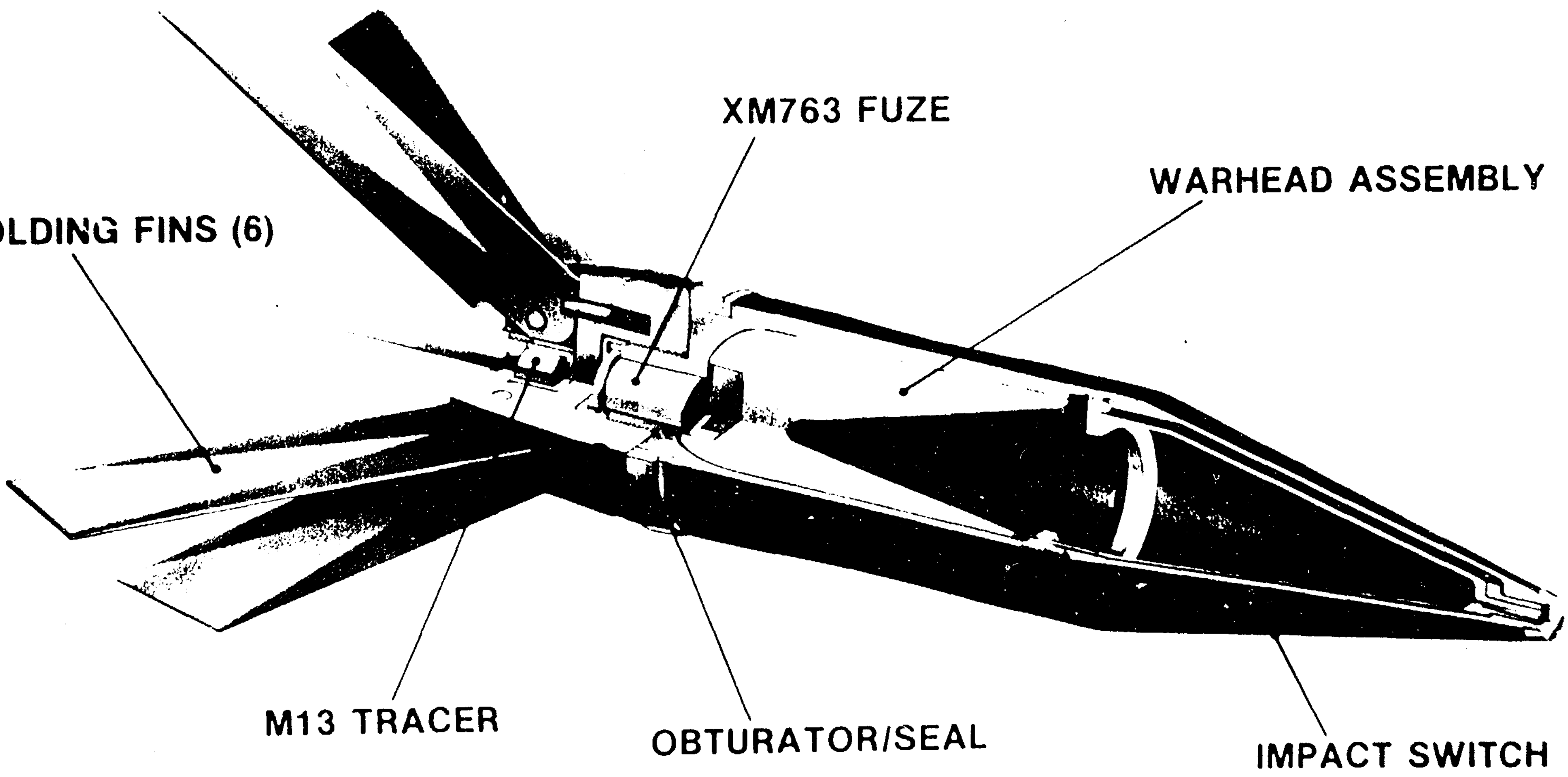


Figure 1. XM815, 105 mm HEAT-MP-T projectile

Preceding Page Blank

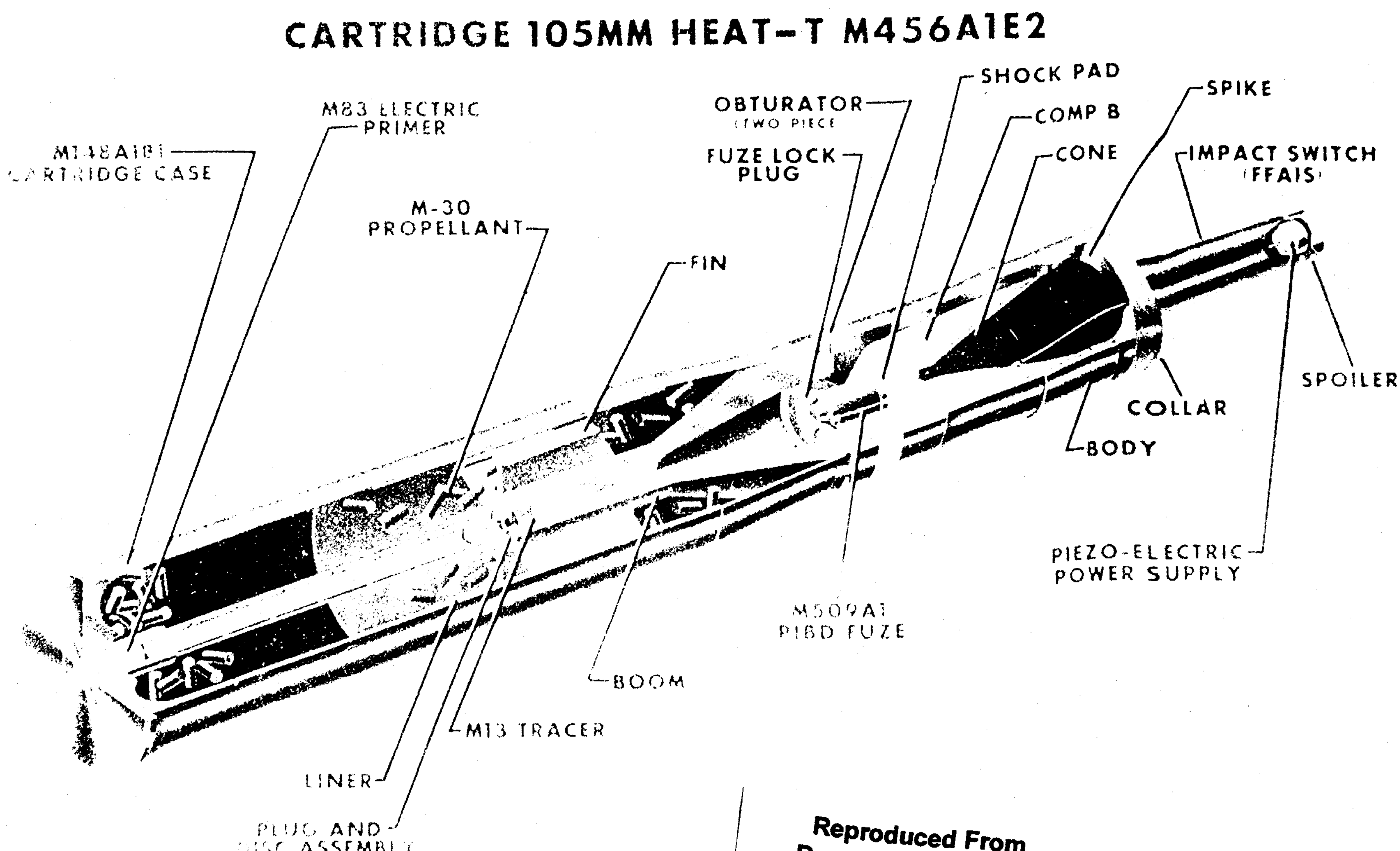


Figure 2. M456A2, 105 mm HEAT-T cartridge

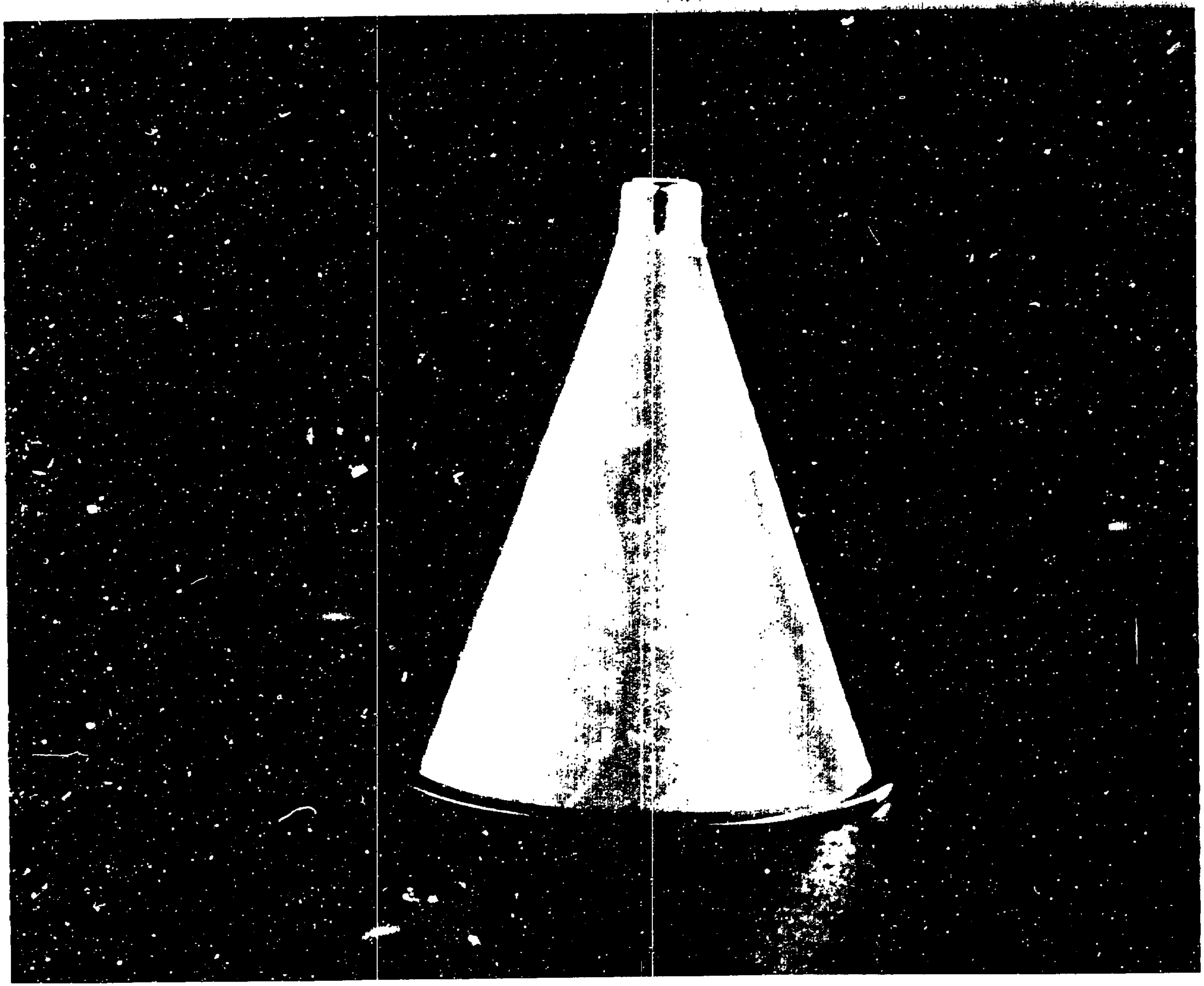


Figure 3. M456A2, 42-degree straight wall liner

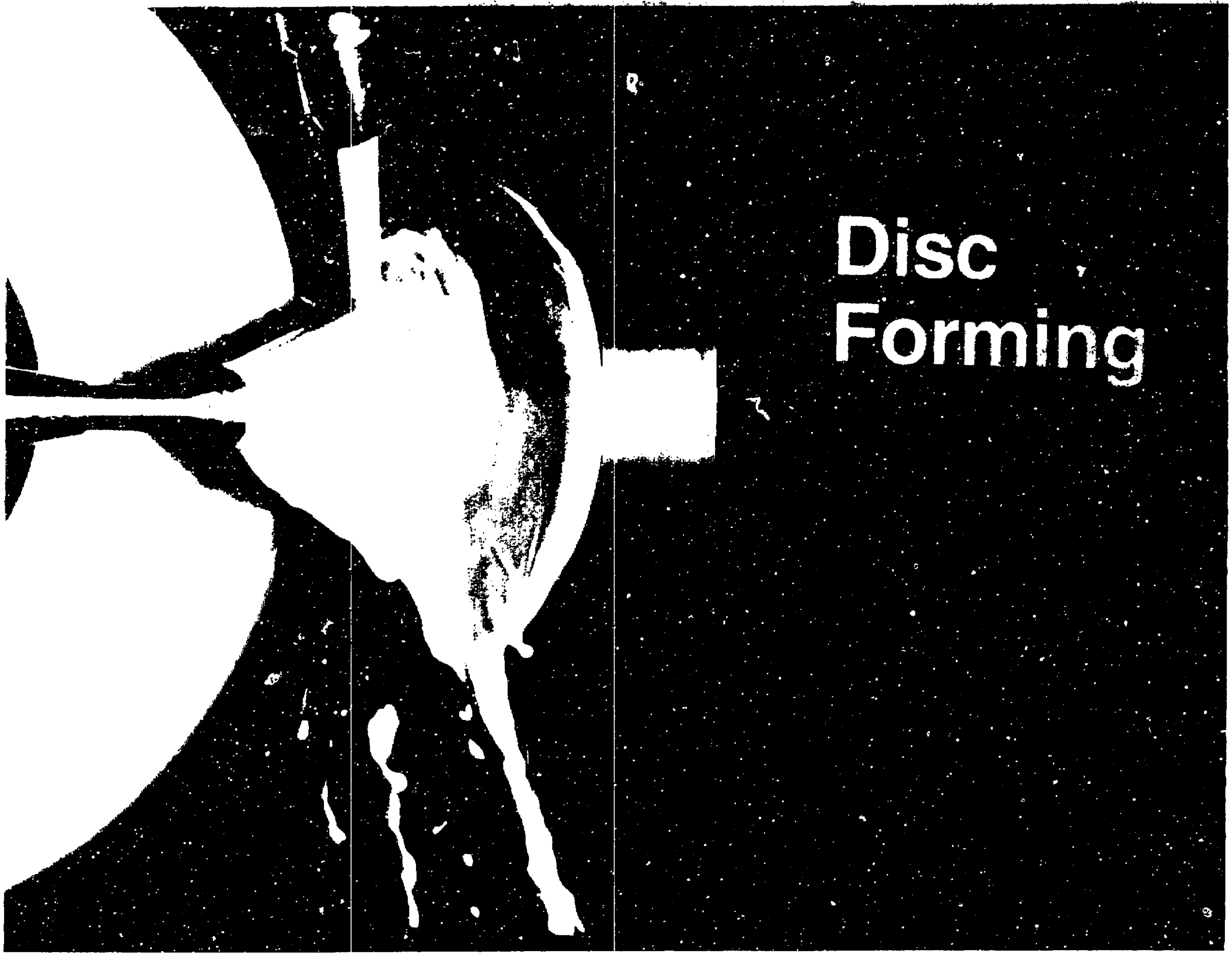
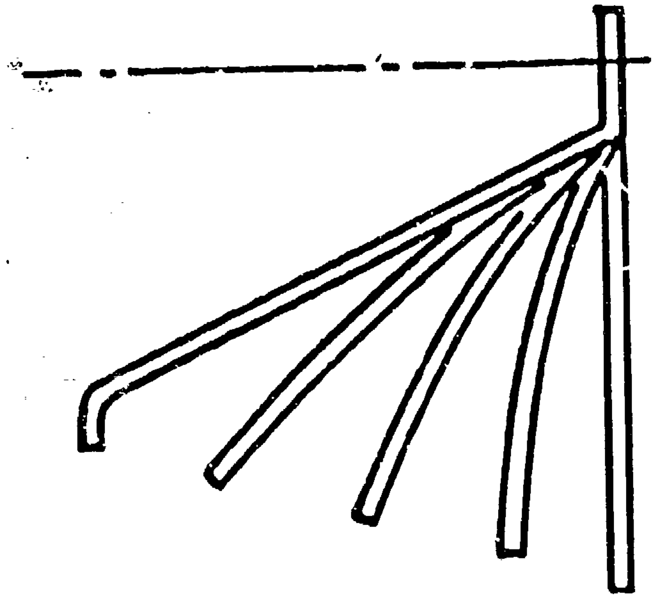
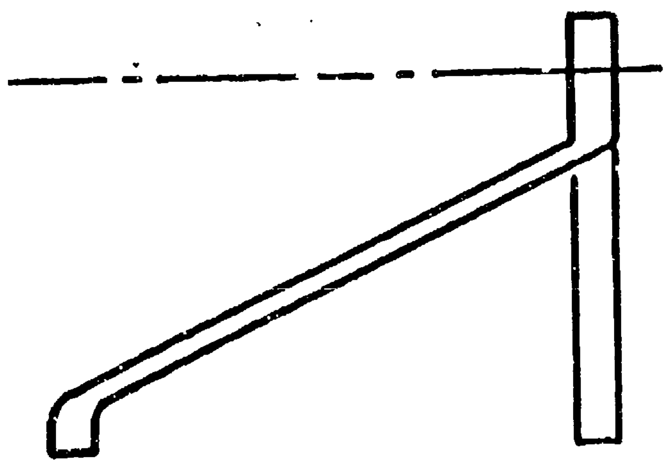


Figure 4. Shear form process



SPINNING



SHEARFORMING

Figure 5. Comparison of spinning and shear forming

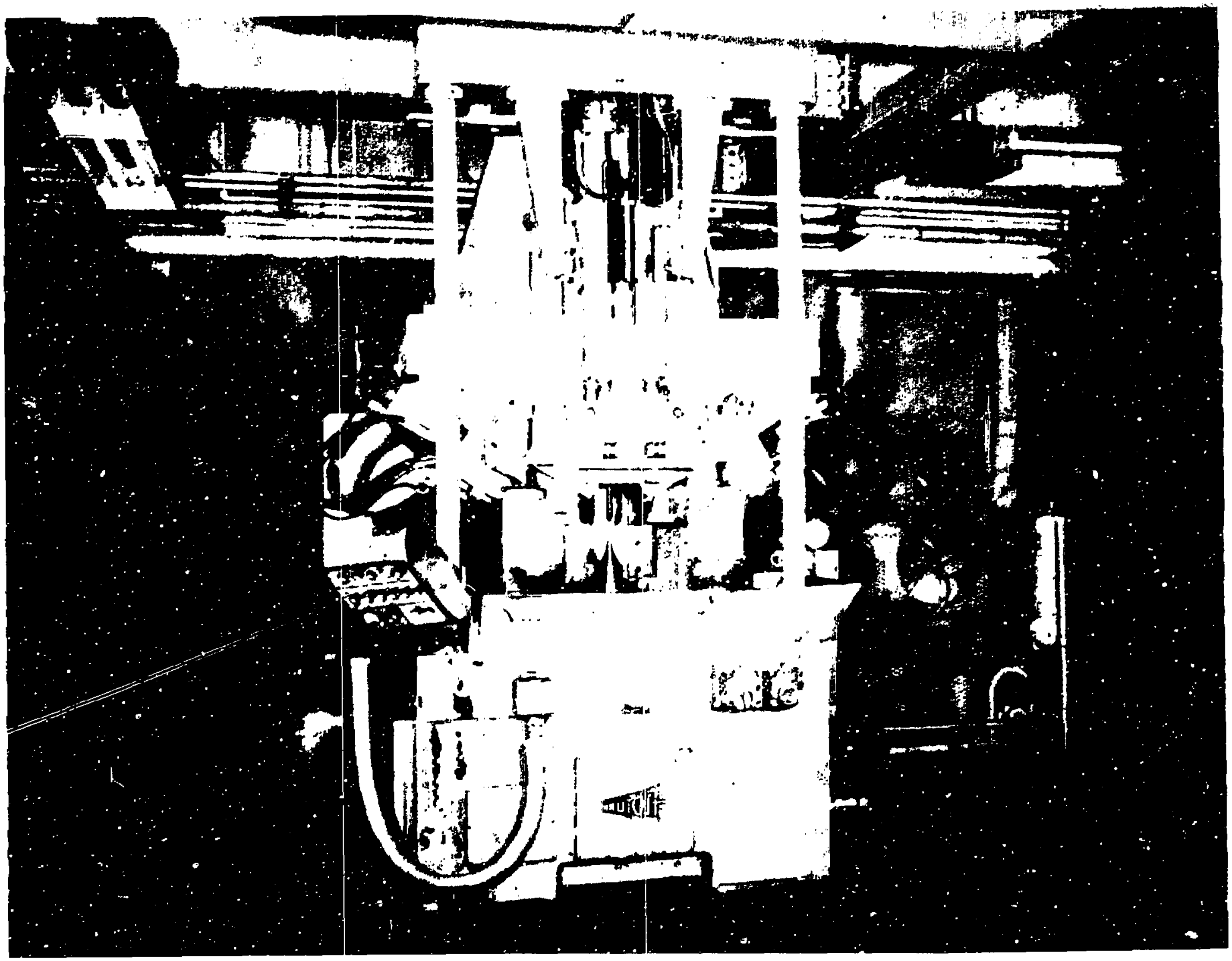


Figure 6. Lodge and Shipley flo-turn equipemnt

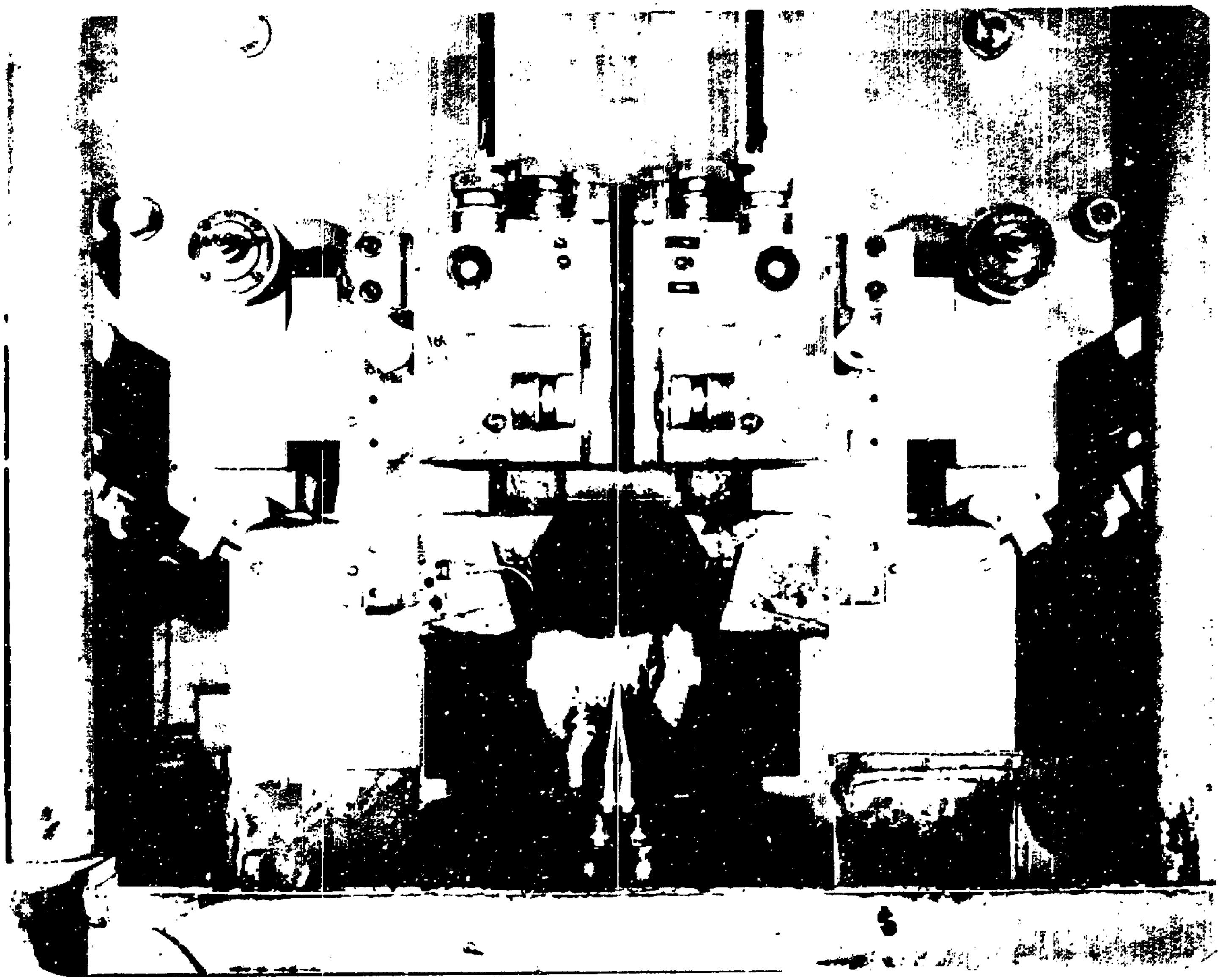


Figure 7. Closeup of Lodge and Shipley flo-turn tooling

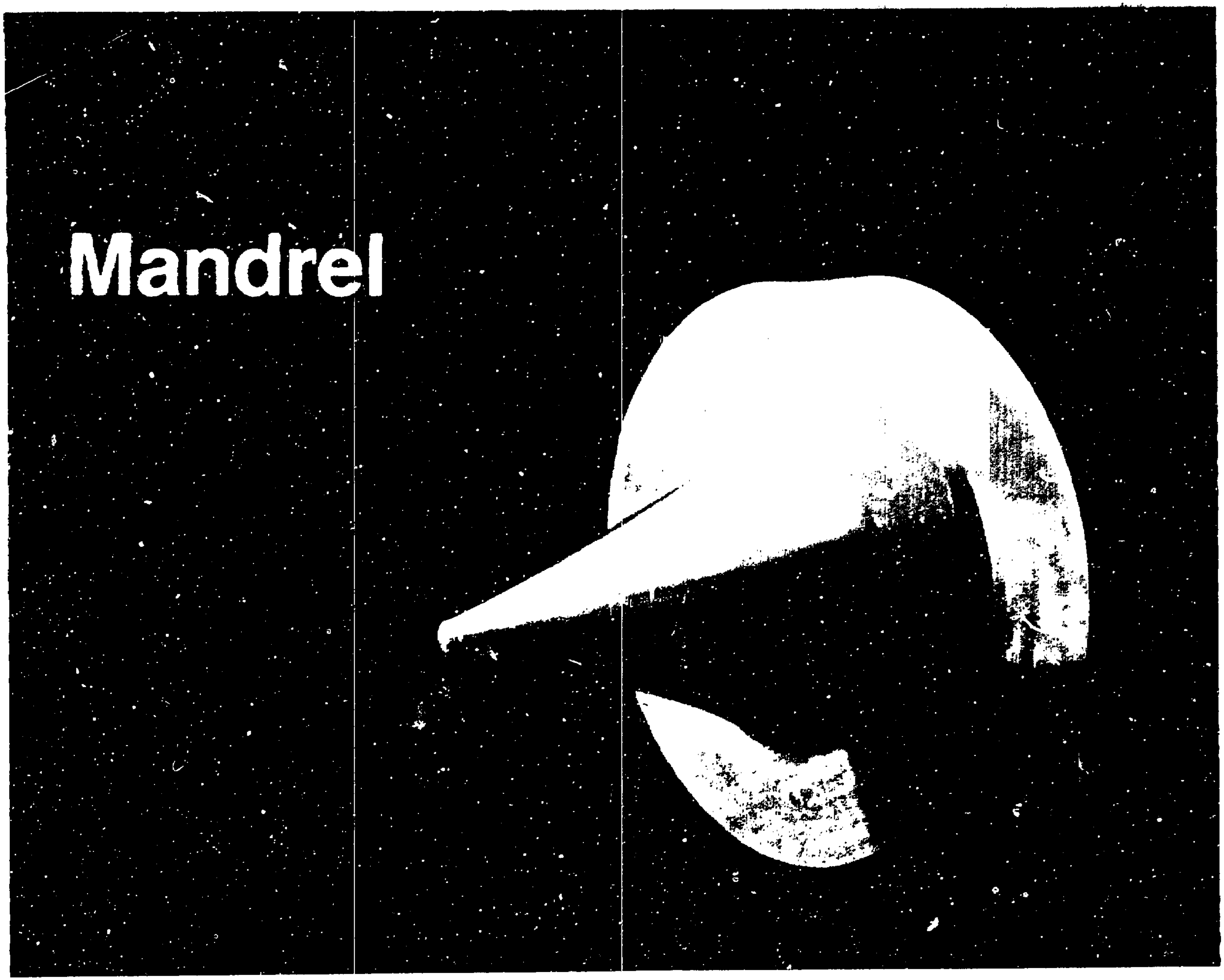


Figure 8. Mandrel

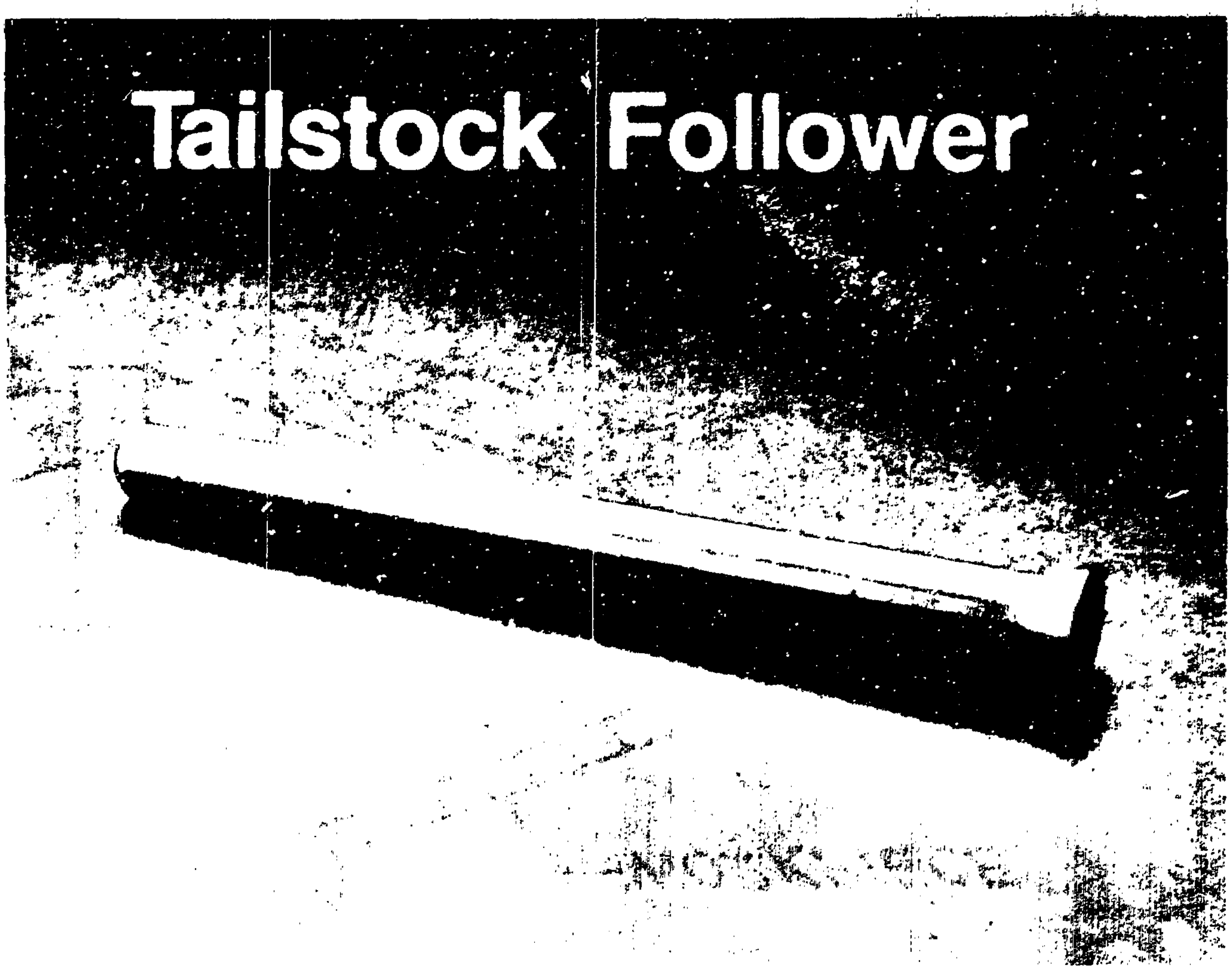


Figure 9. Tailstock follower

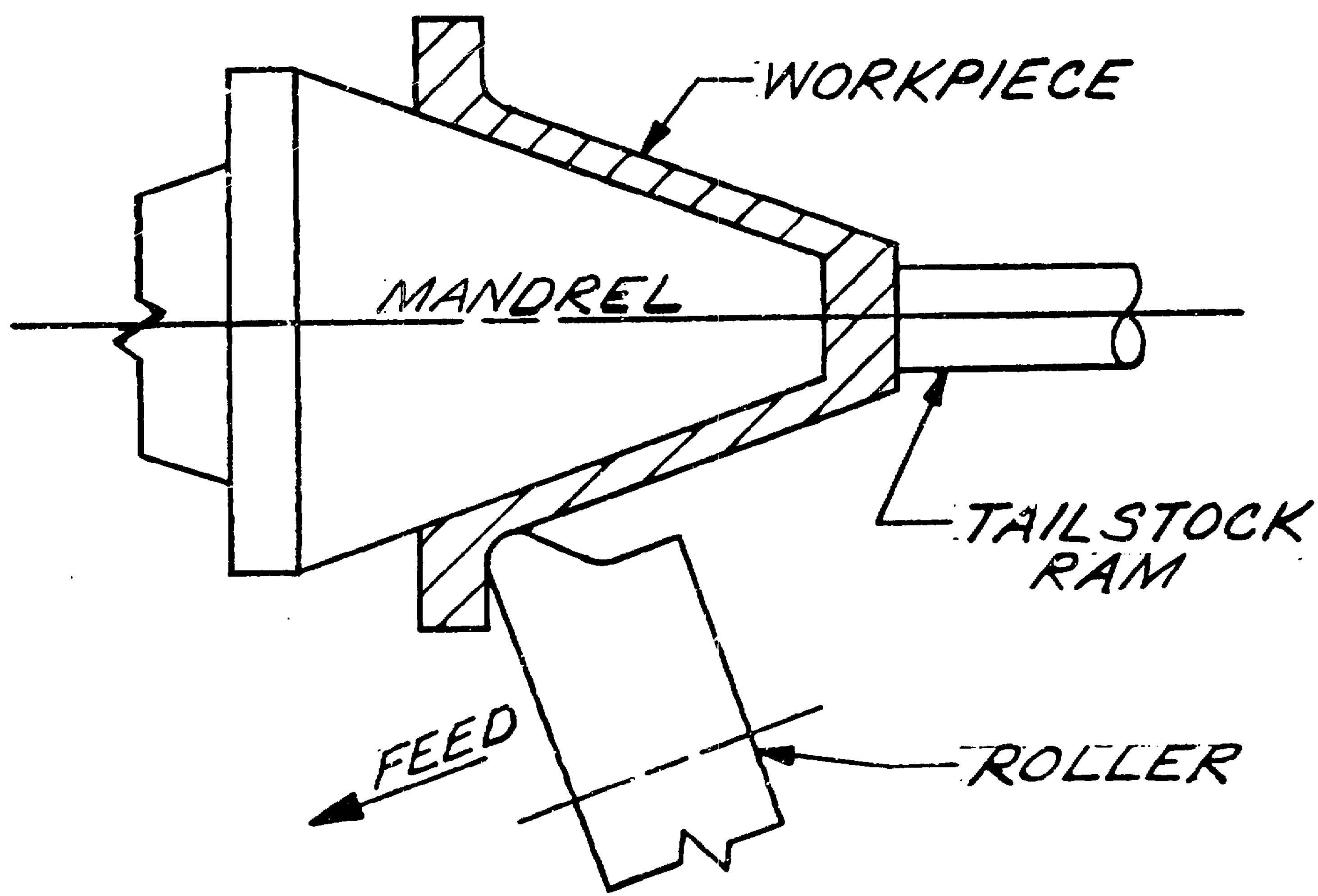


Figure 10. Shear forming operation

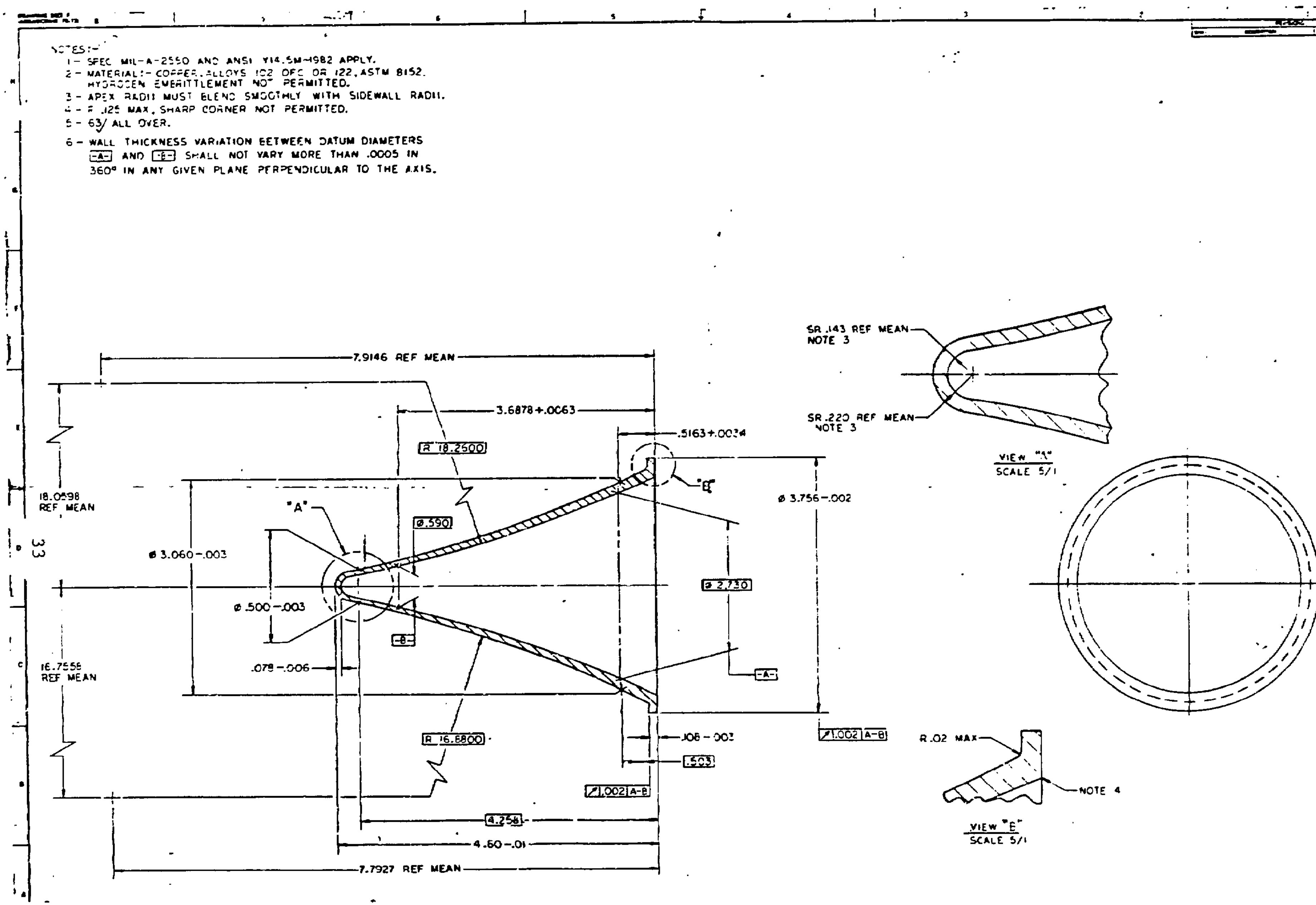


Figure 11. B3 trumpet liner drawing

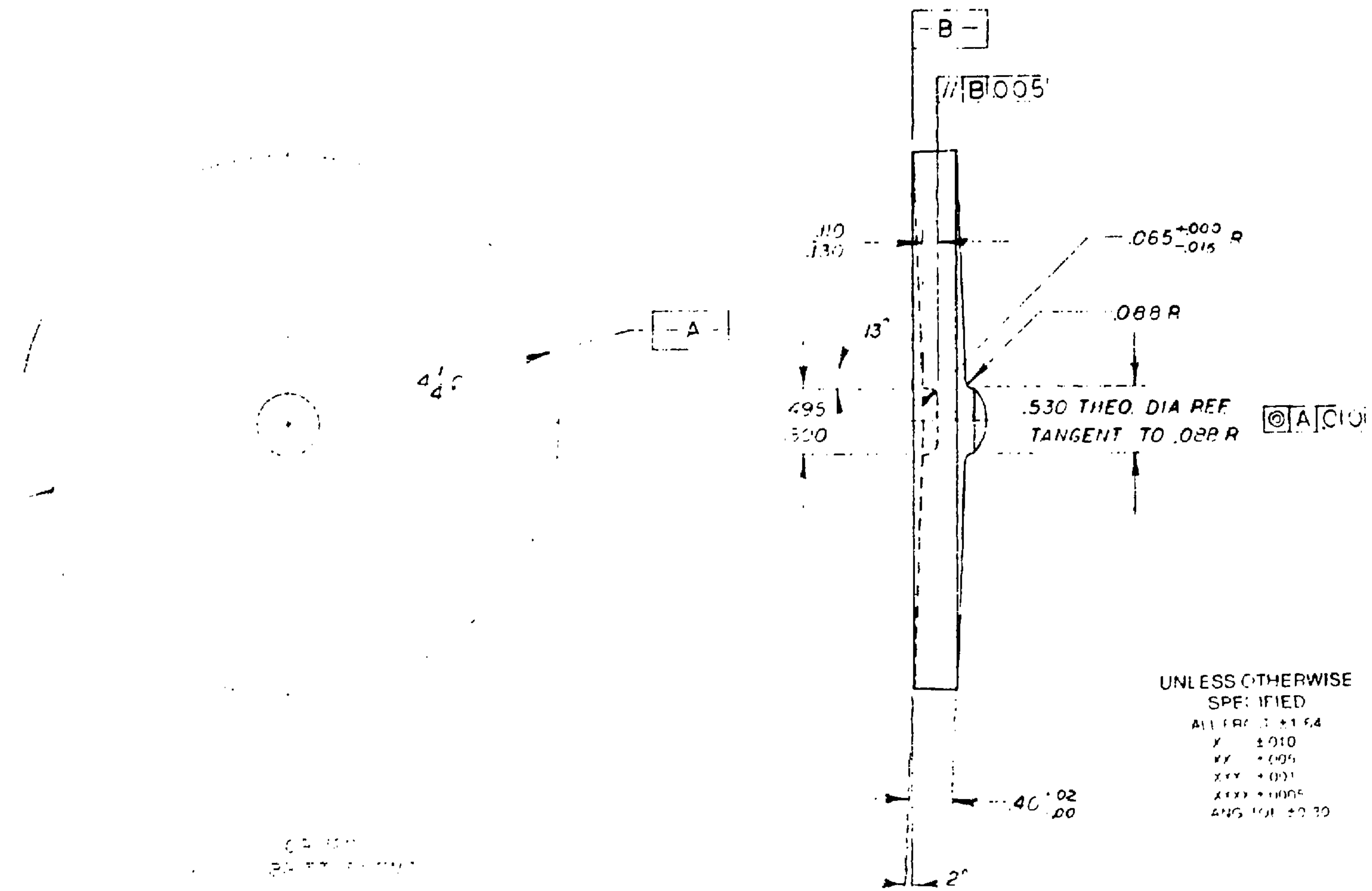


Figure 12. Starting blank preform, groups A, C, D, F, and G

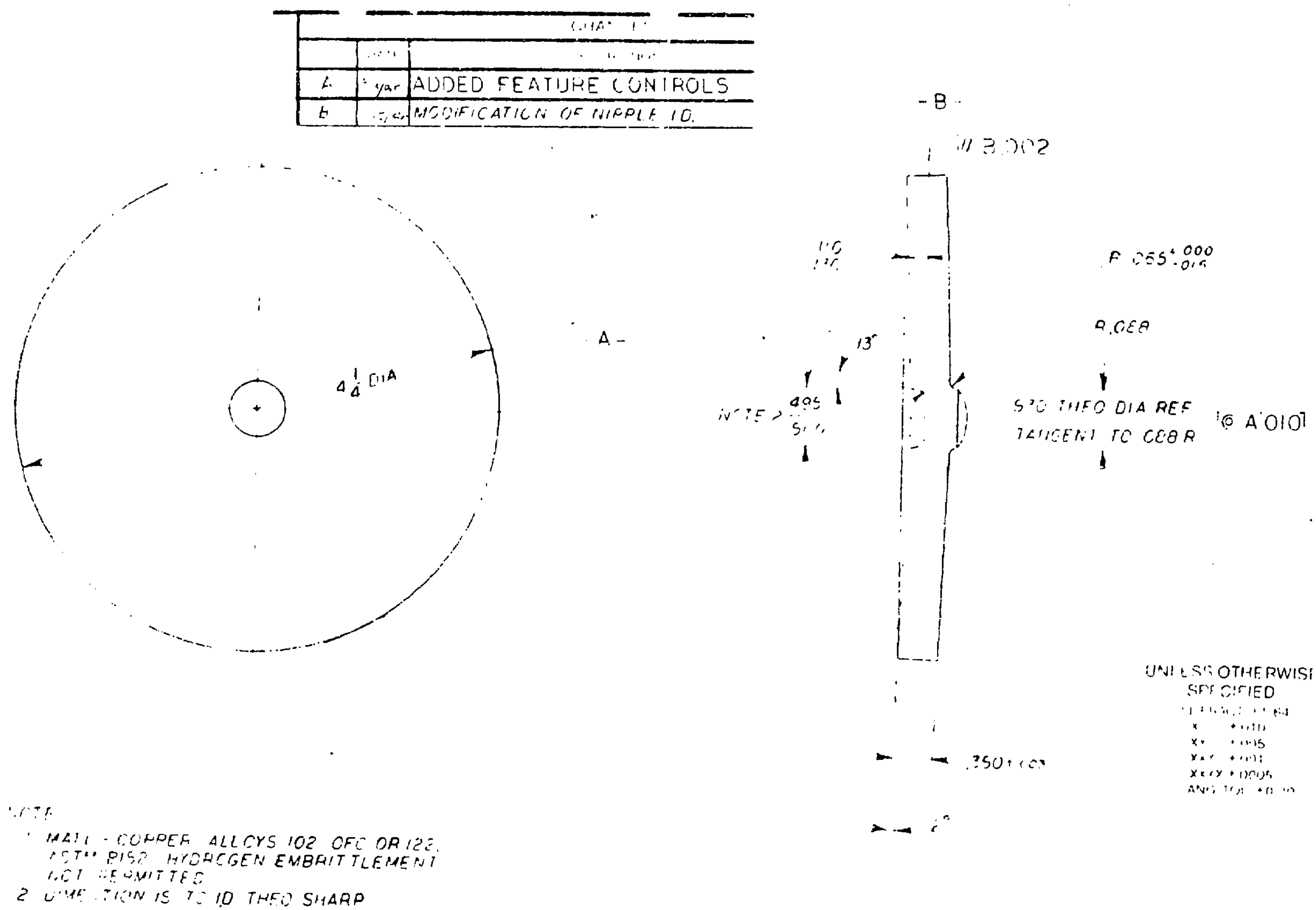


Figure 13. Starting blank preform, groups B and E

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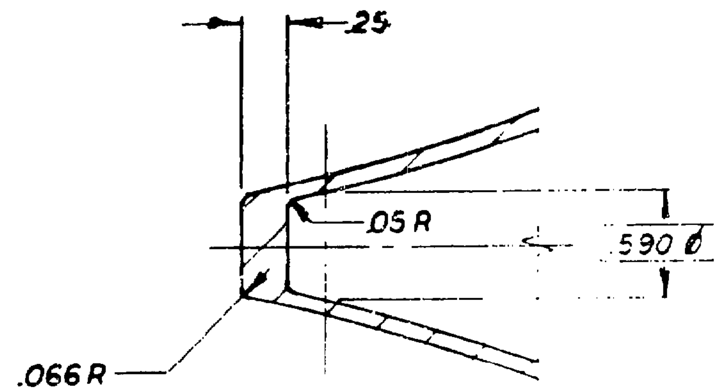


Figure 14. As-formed liner nose, groups D and G

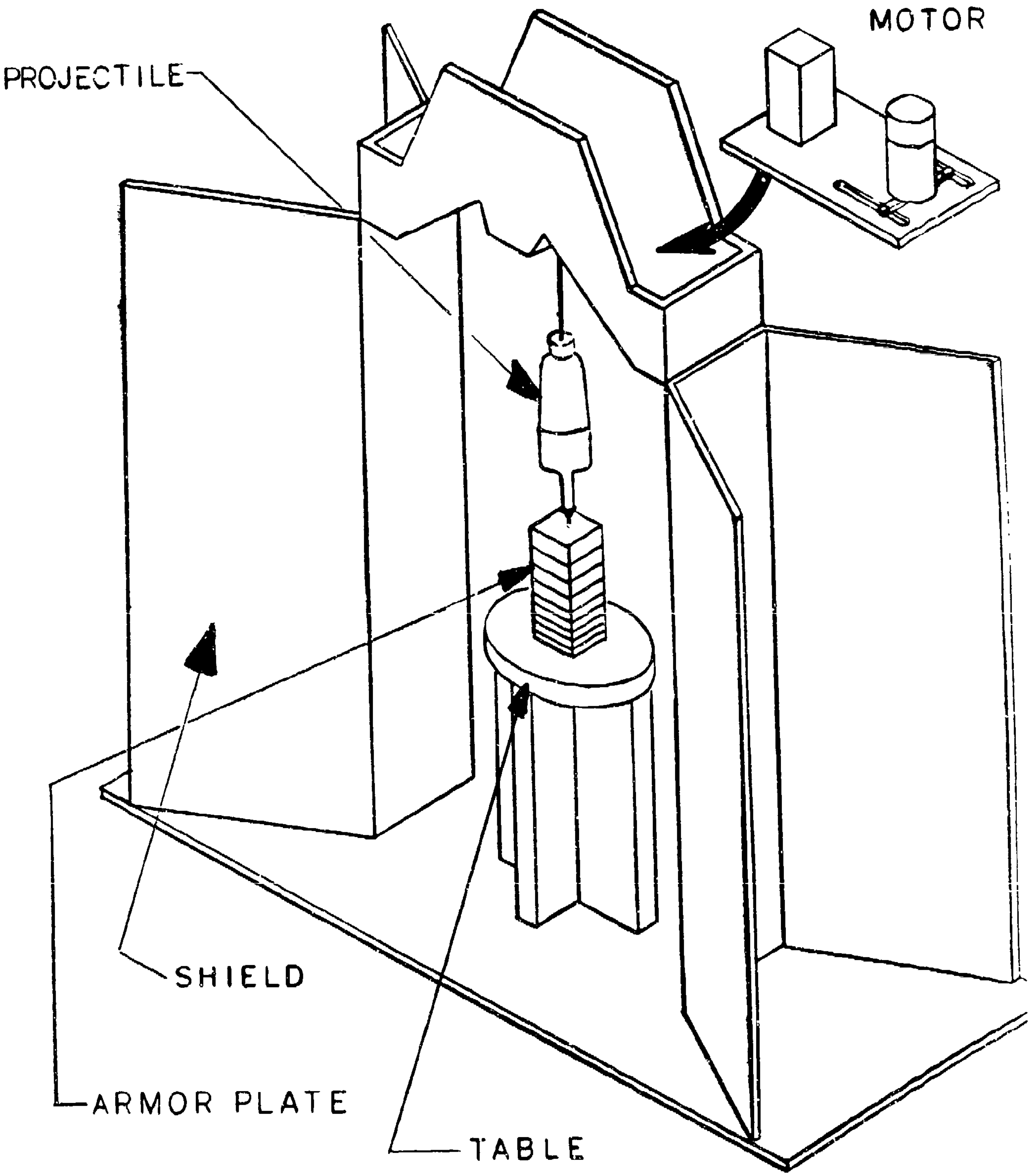


Figure 15. Milan AAP static penetration test stand

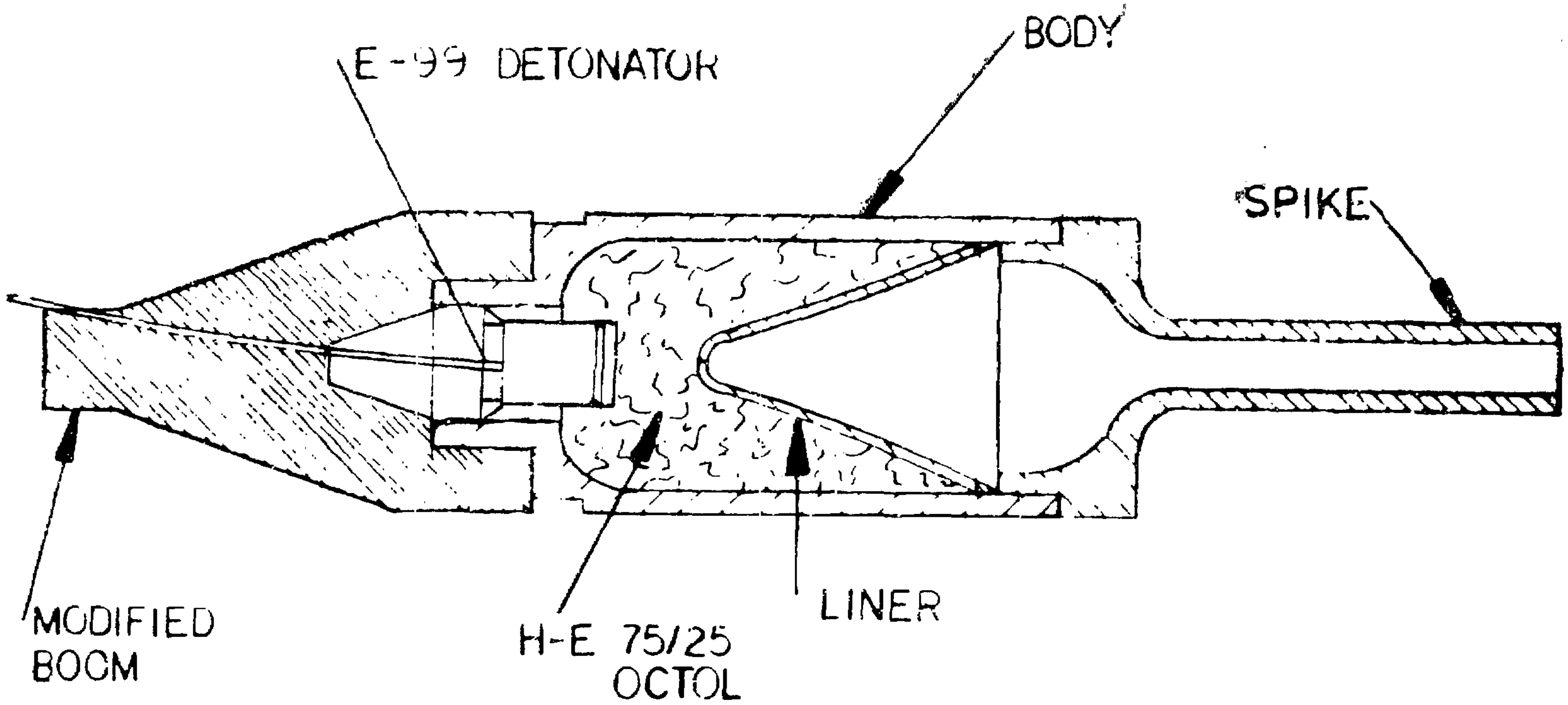


Figure 16. Static penetration test warhead

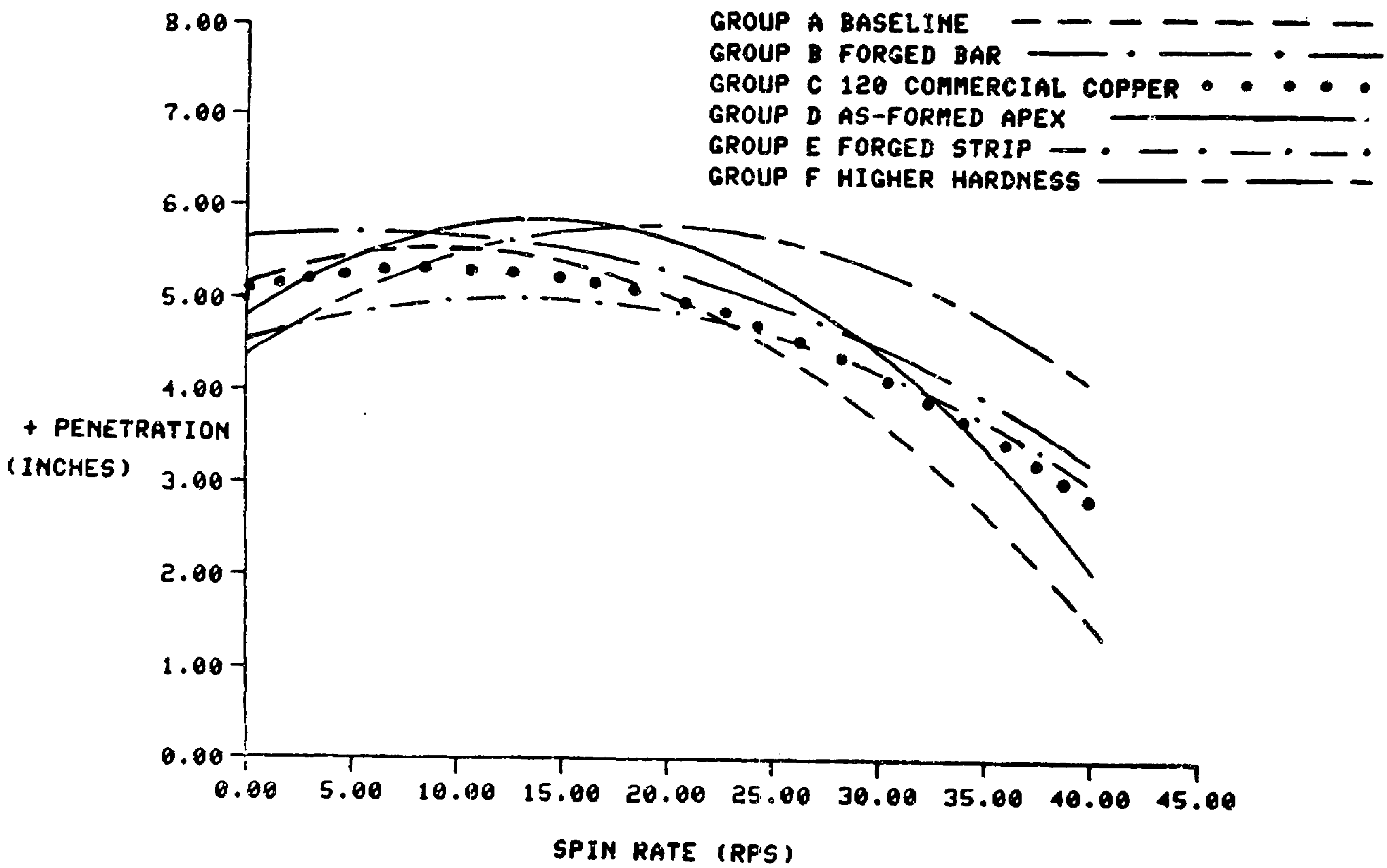


Figure 17. Static penetration results, groups A through F

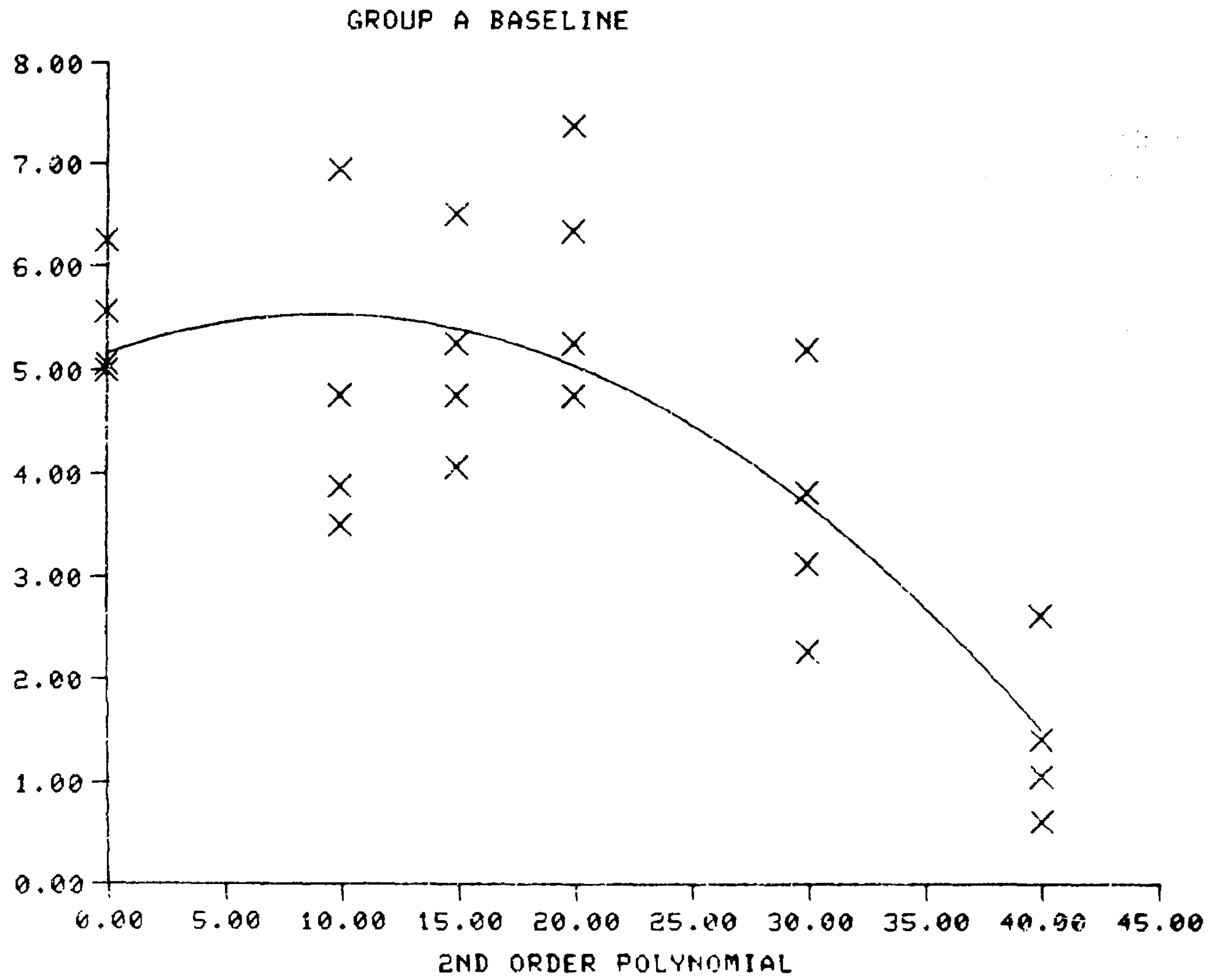


Figure 18. Static penetration results, group A

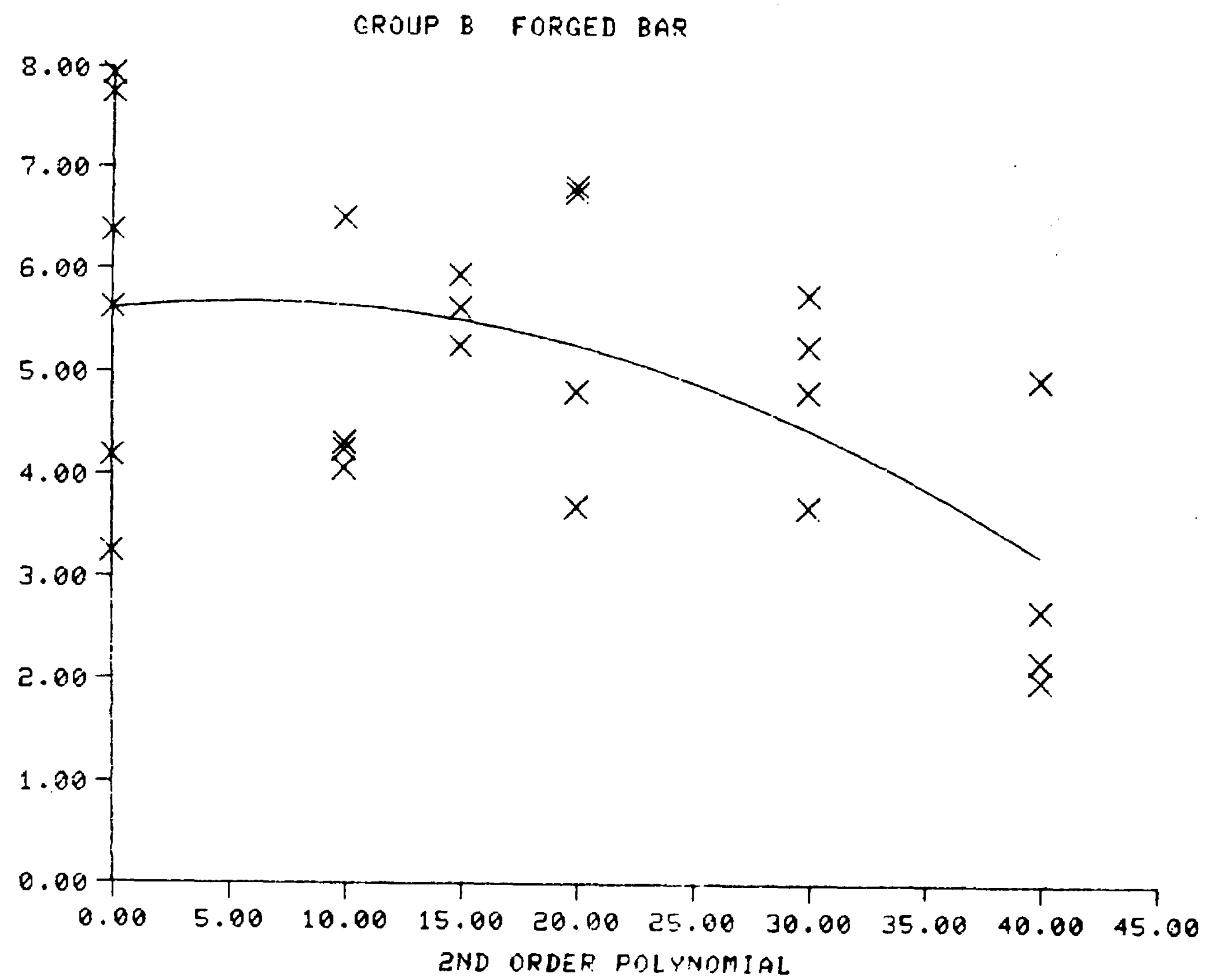


Figure 19. Static penetration results, group B

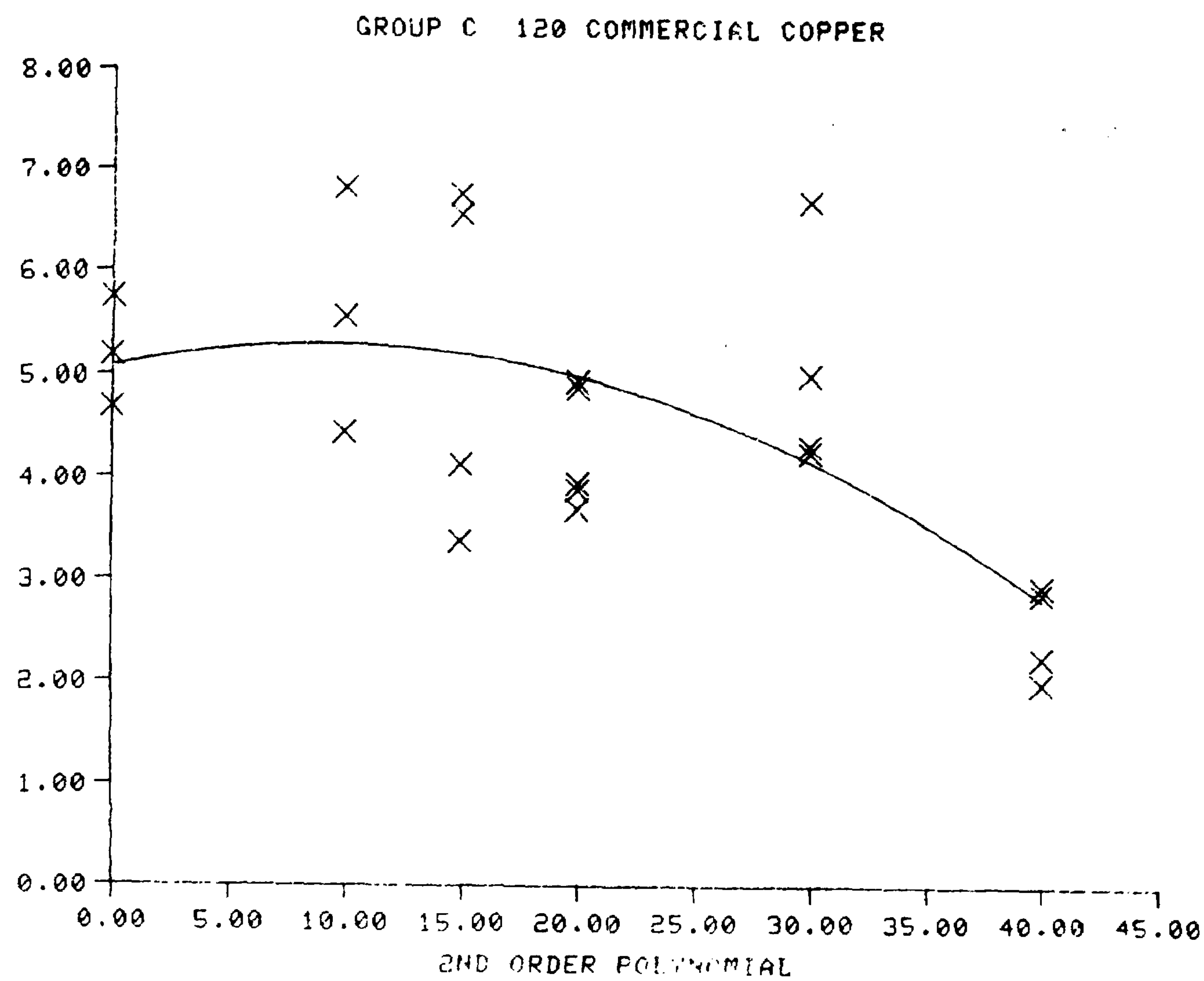


Figure 20. Static penetration results, group C

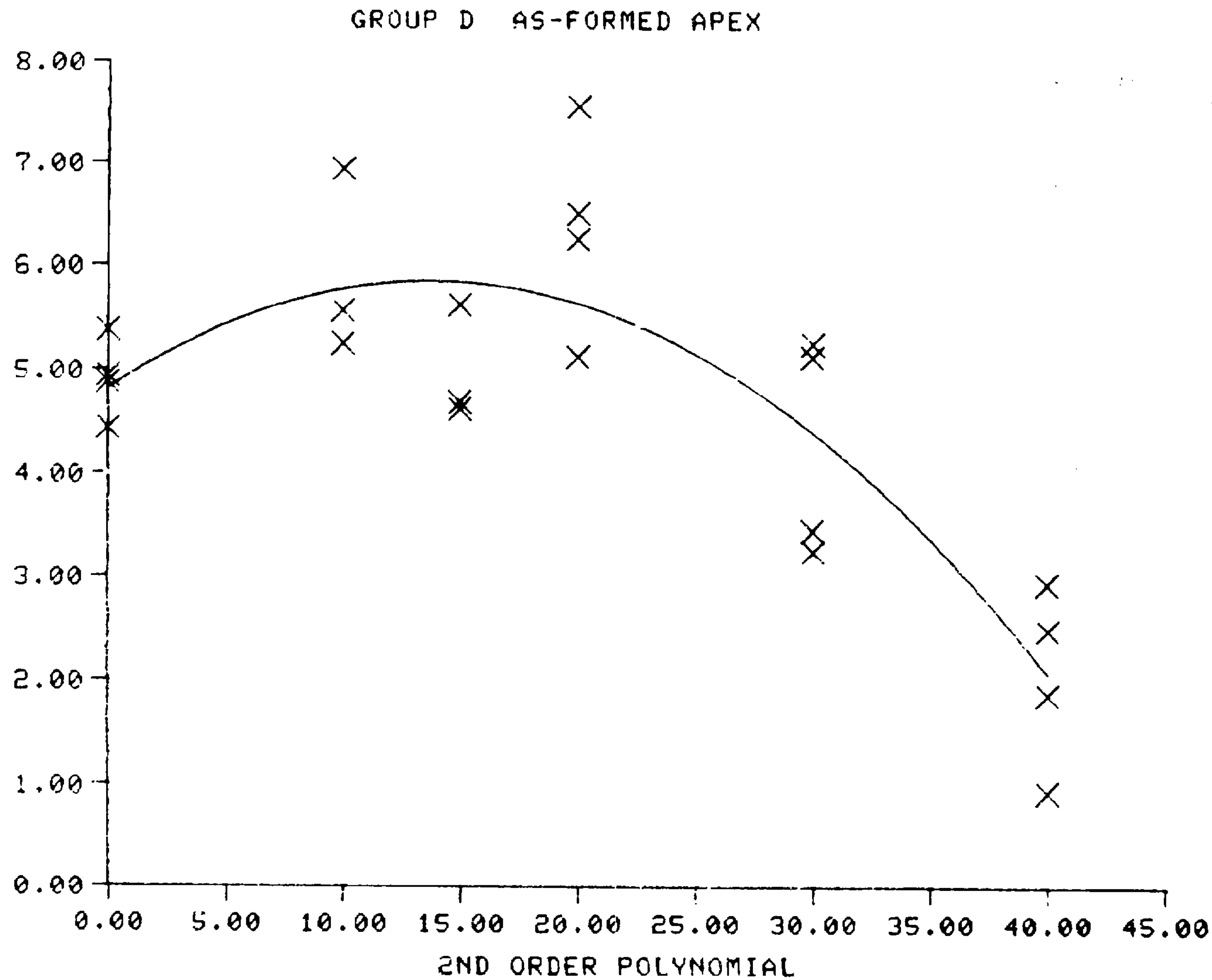


Figure 21. Static penetration results, group D

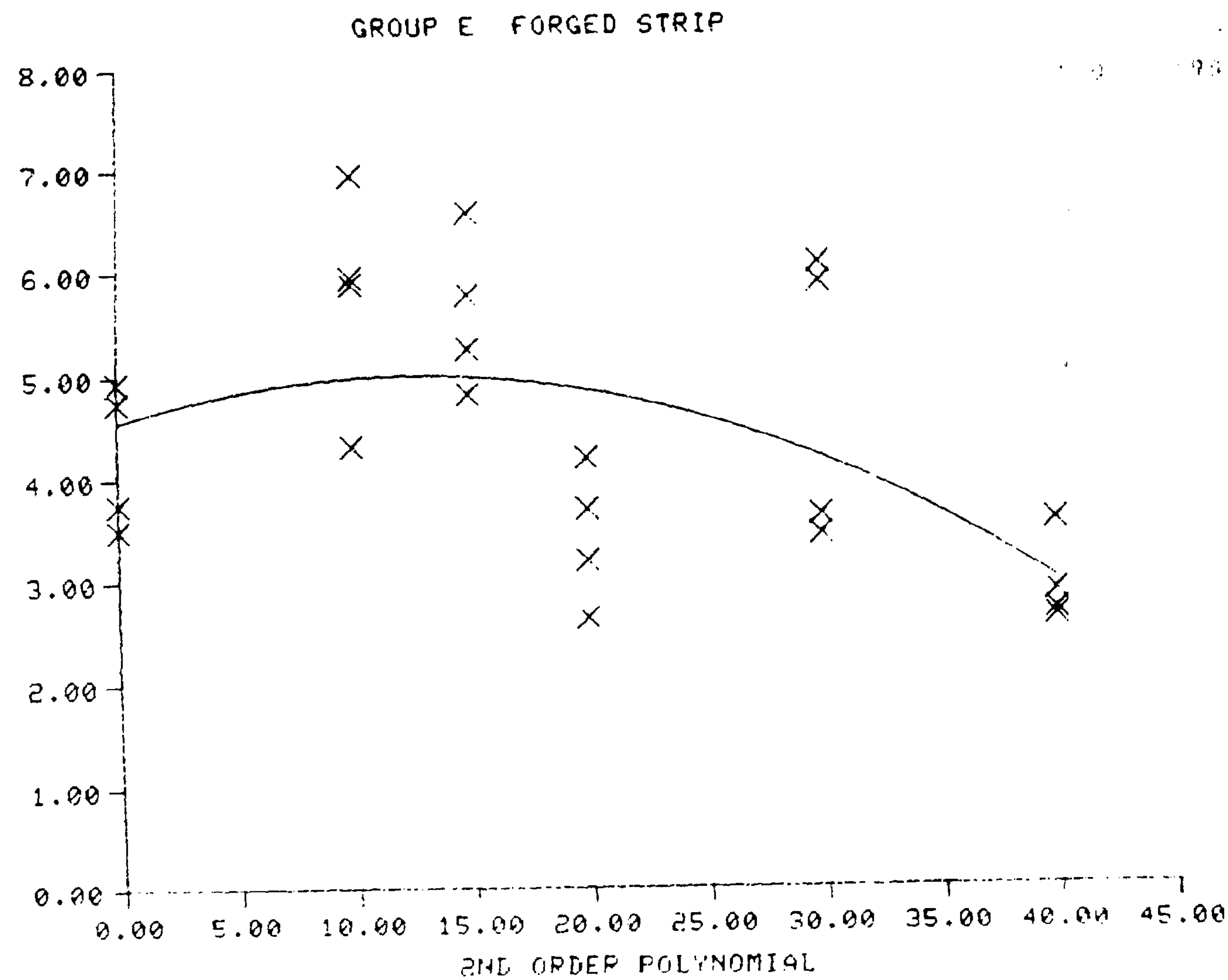


Figure 22. Static penetration results. group E

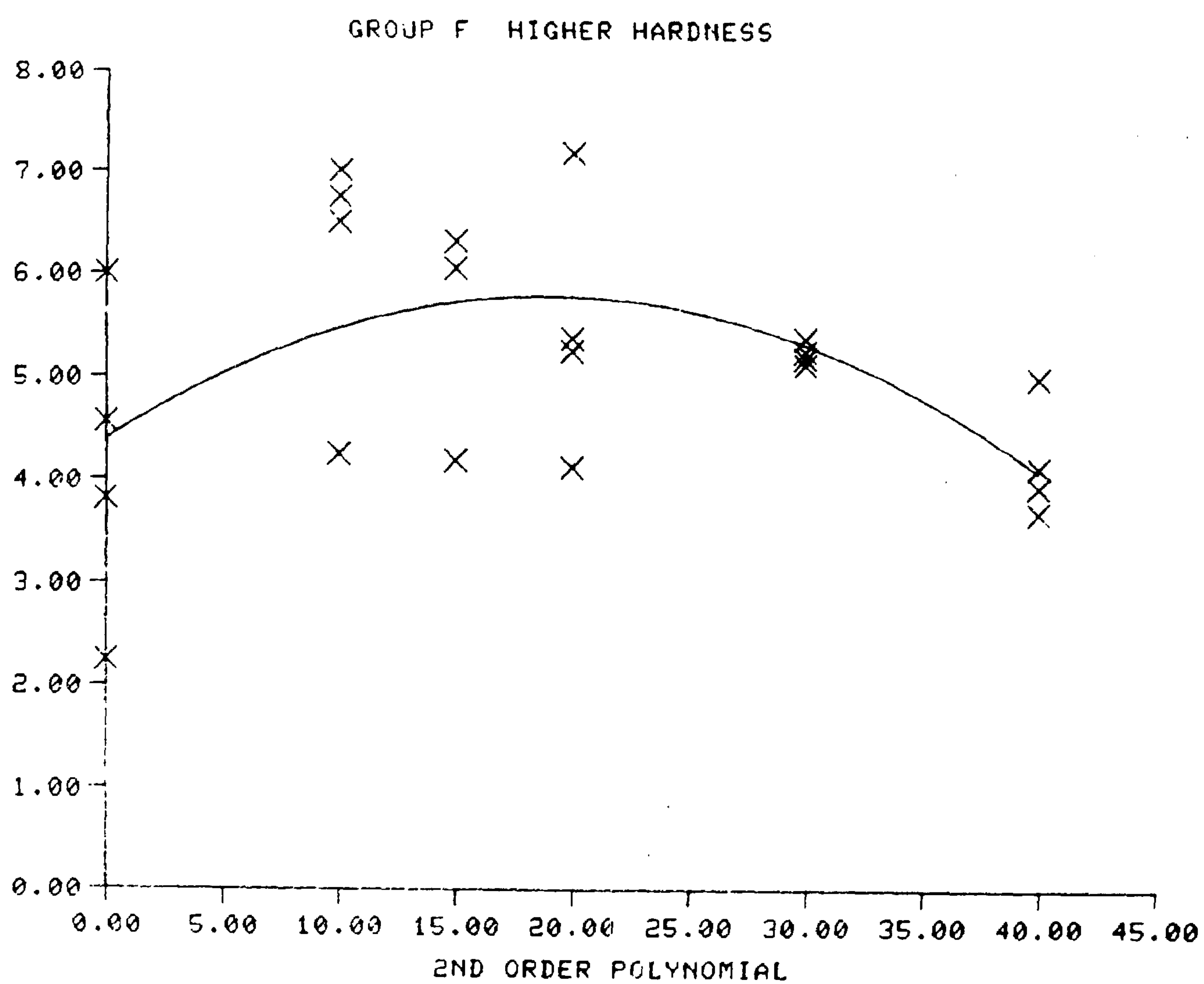


Figure 23. Static penetration results, group F

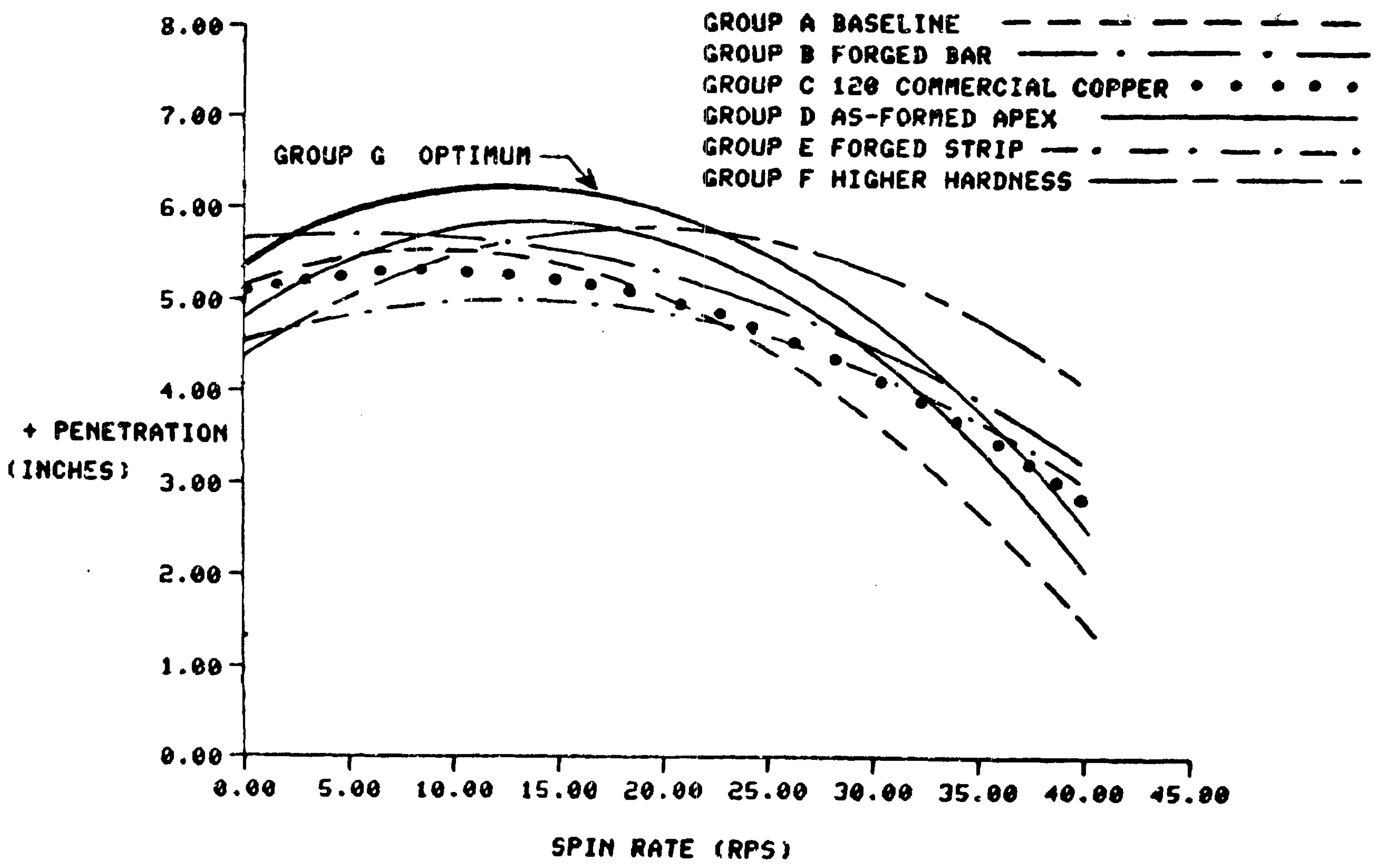


Figure 24. Static penetration results, groups A through G

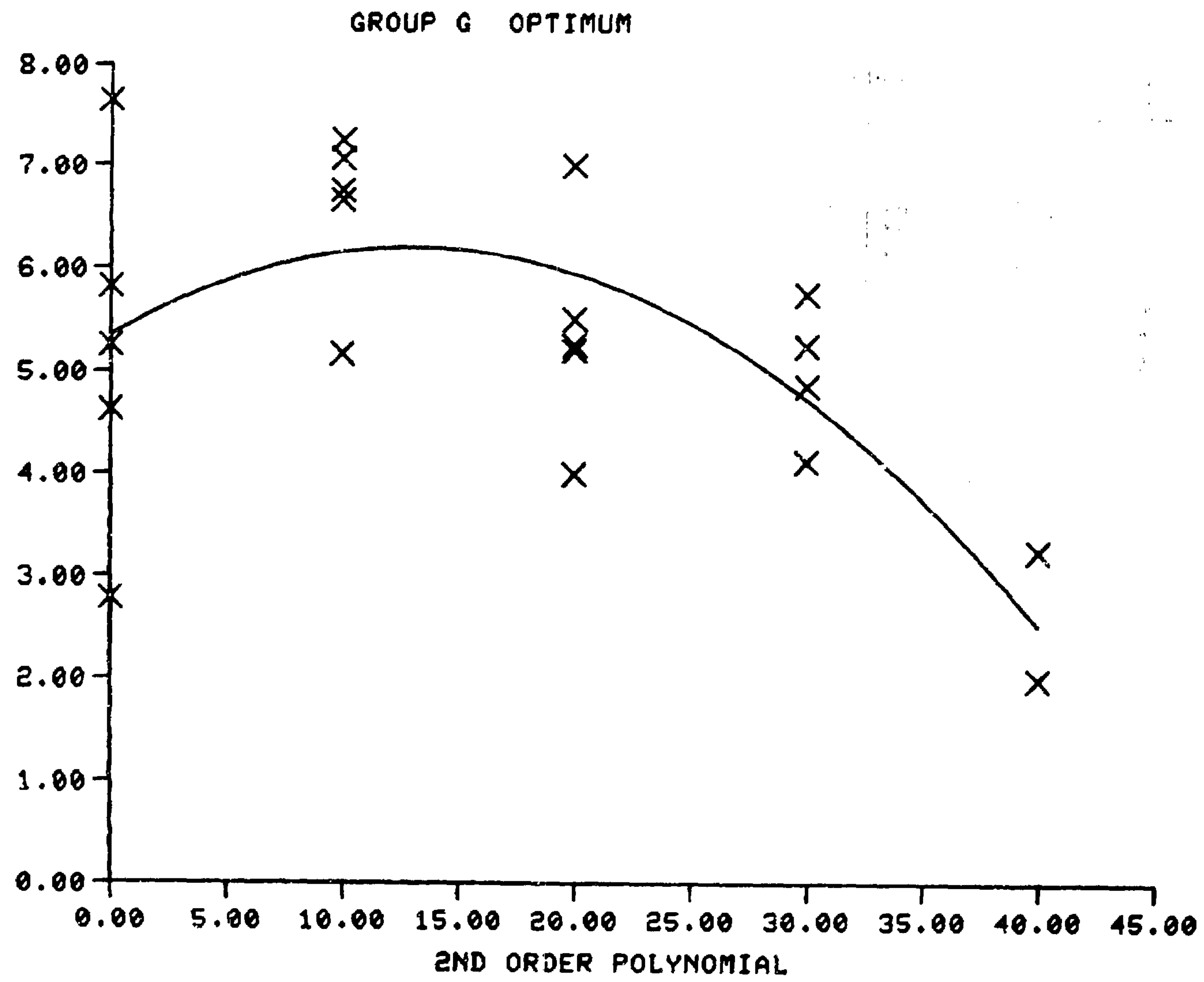


Figure 25. Static penetration results, group G

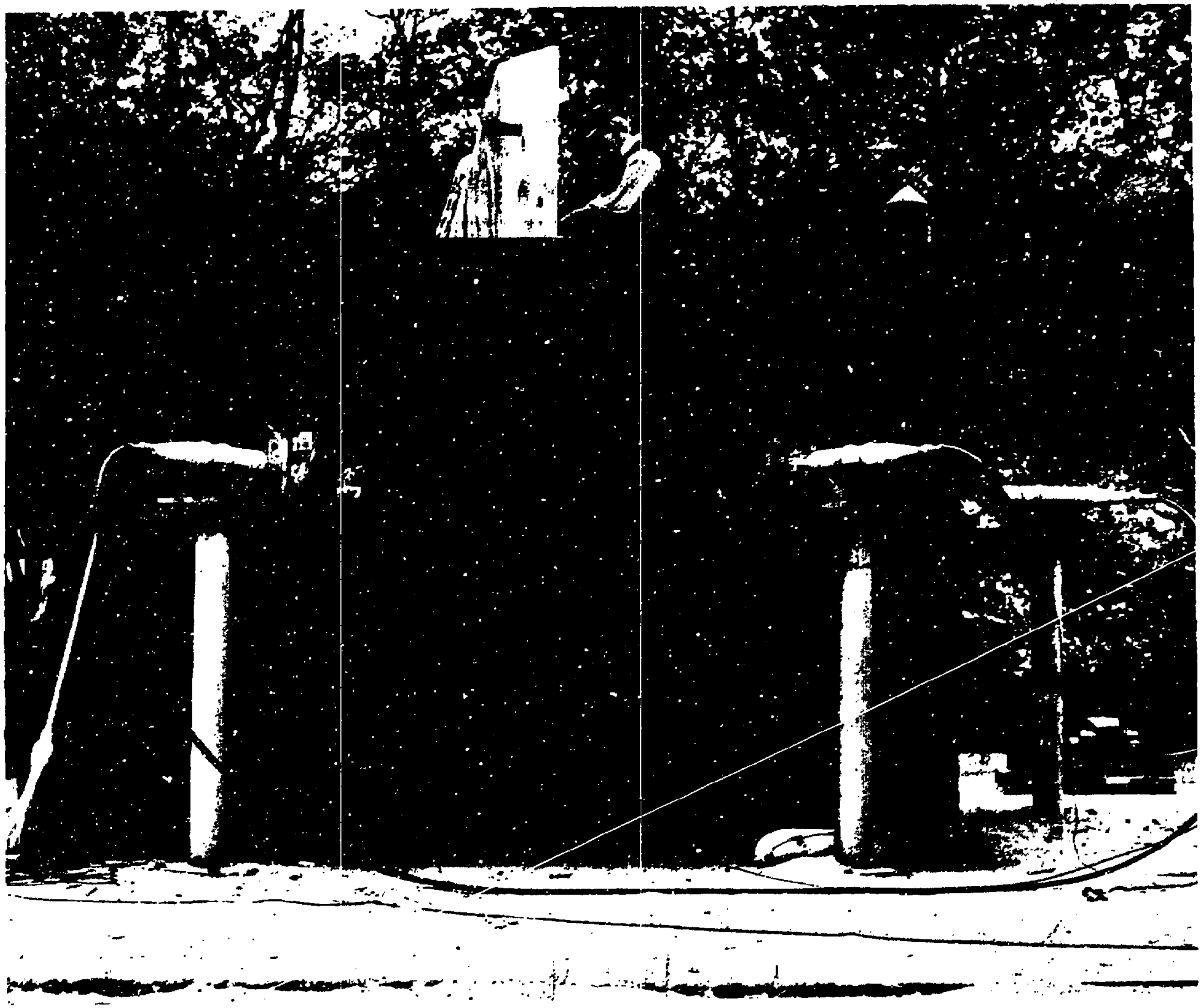


Figure 26. ARDEC triple-flash radiography test facility

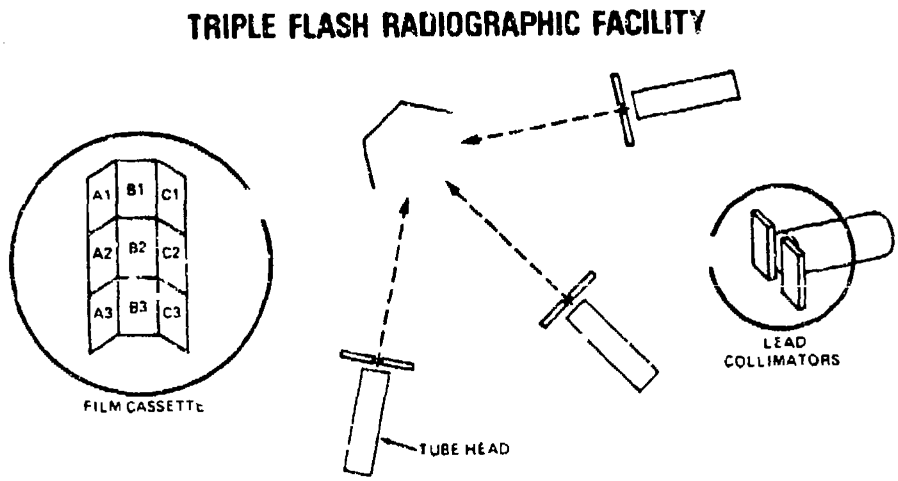


Figure 27. ARDEC triple-flash radiography test facility

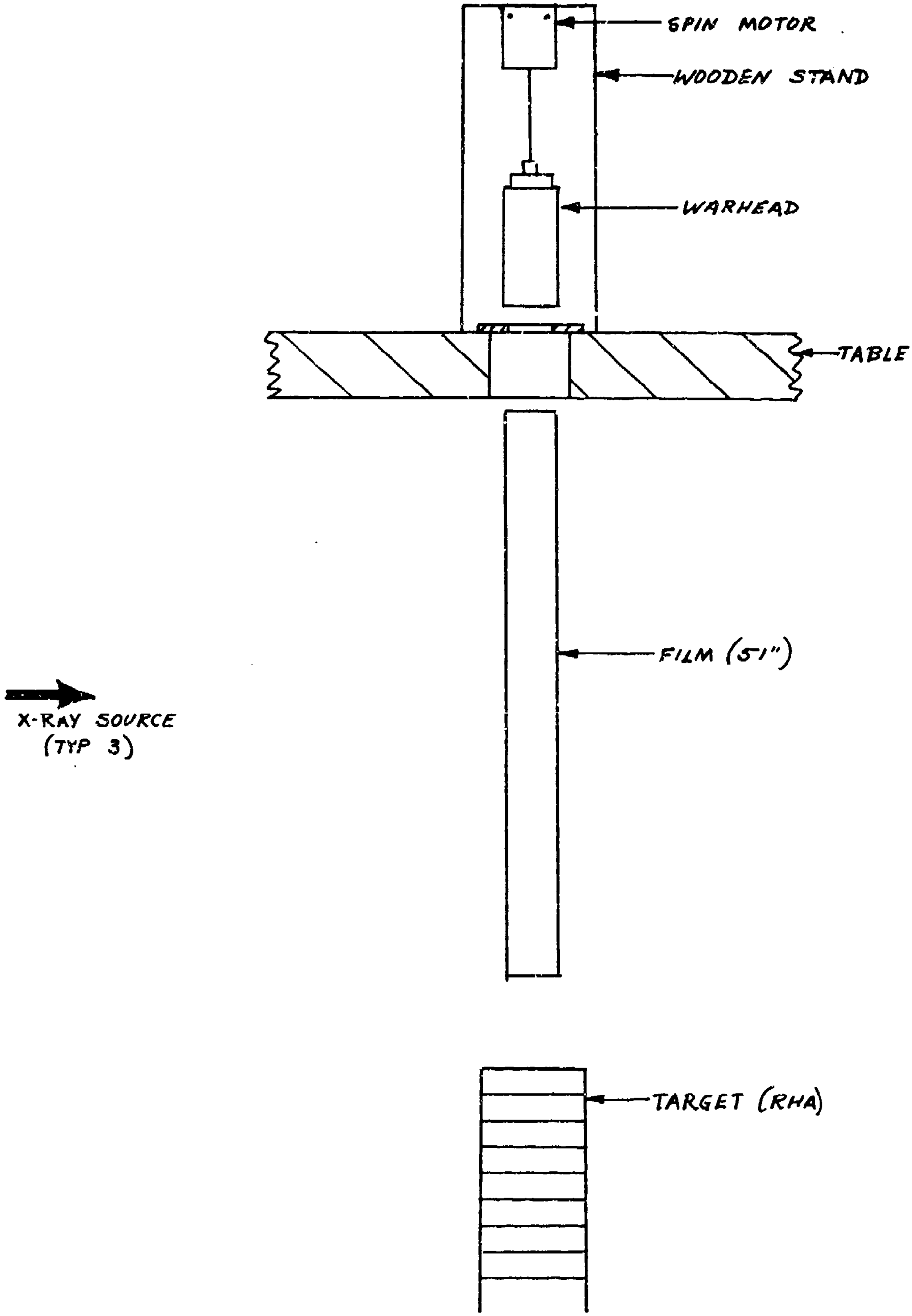


Figure 28. ARDEC triple-flash radiography test setup

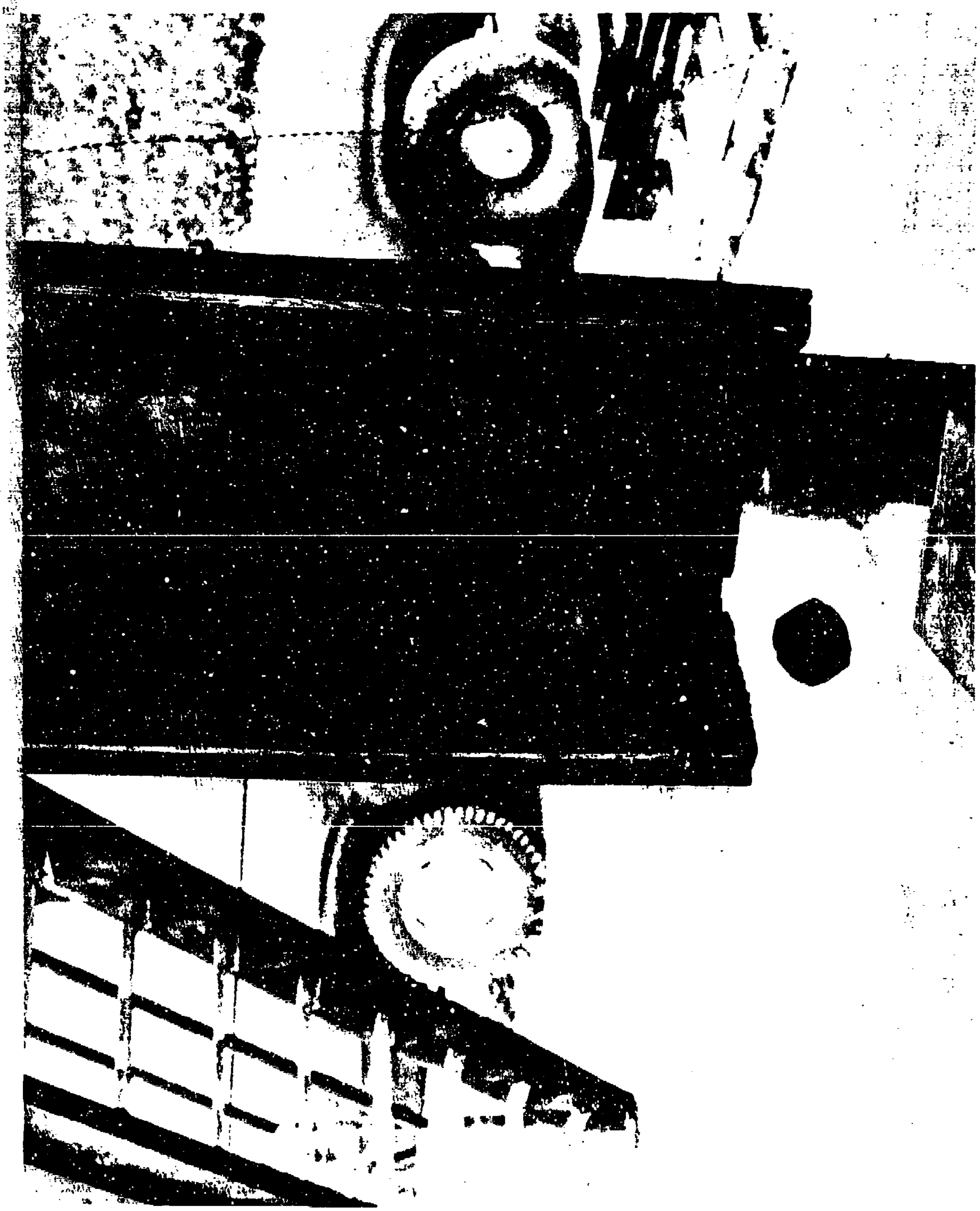


Figure 29. X-ray film cassettes

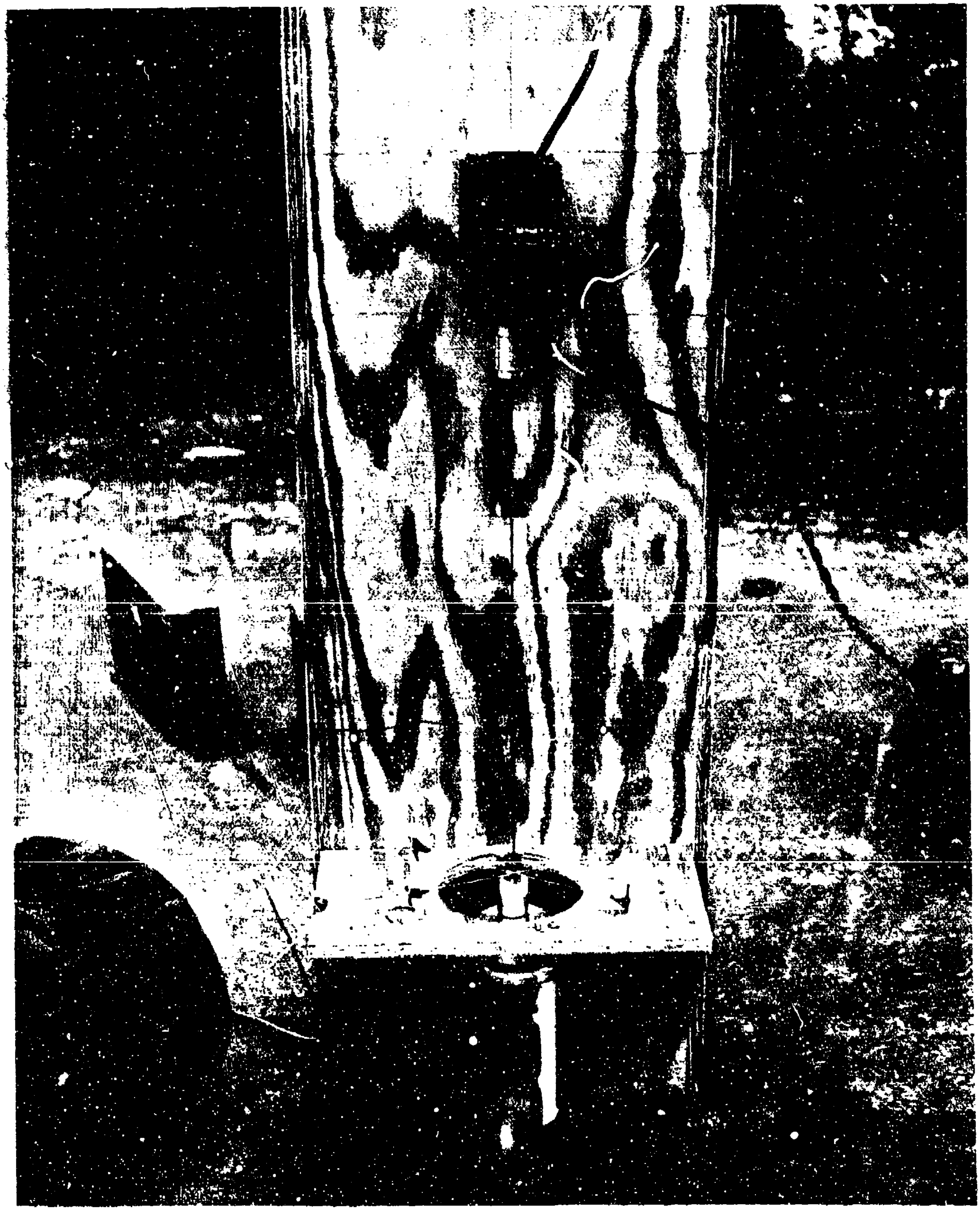


Figure 30. Wooden test stand and motor

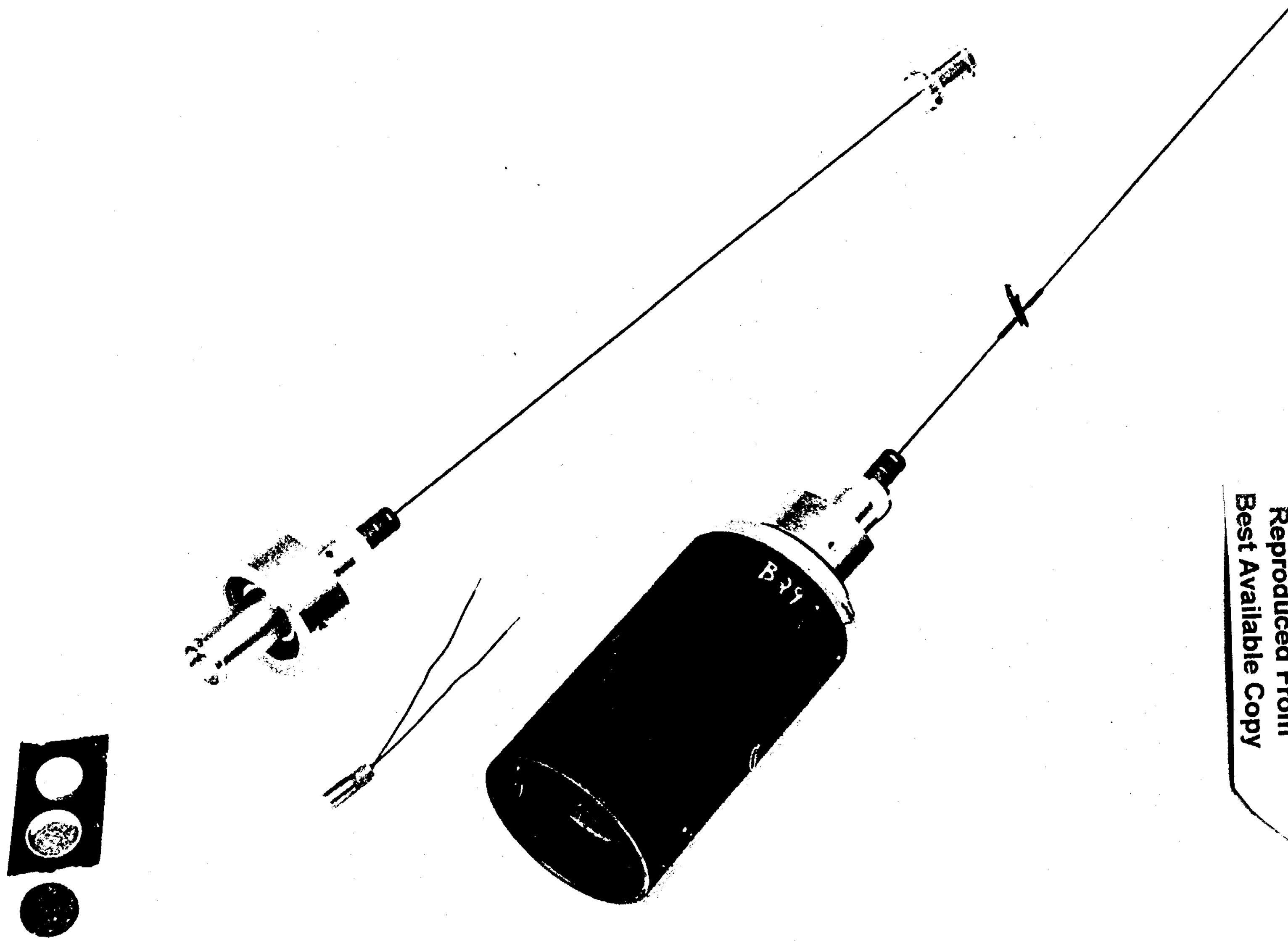


Figure 31. Spin adapter and assembled warhead

Figure 32. RHA steel target after firing

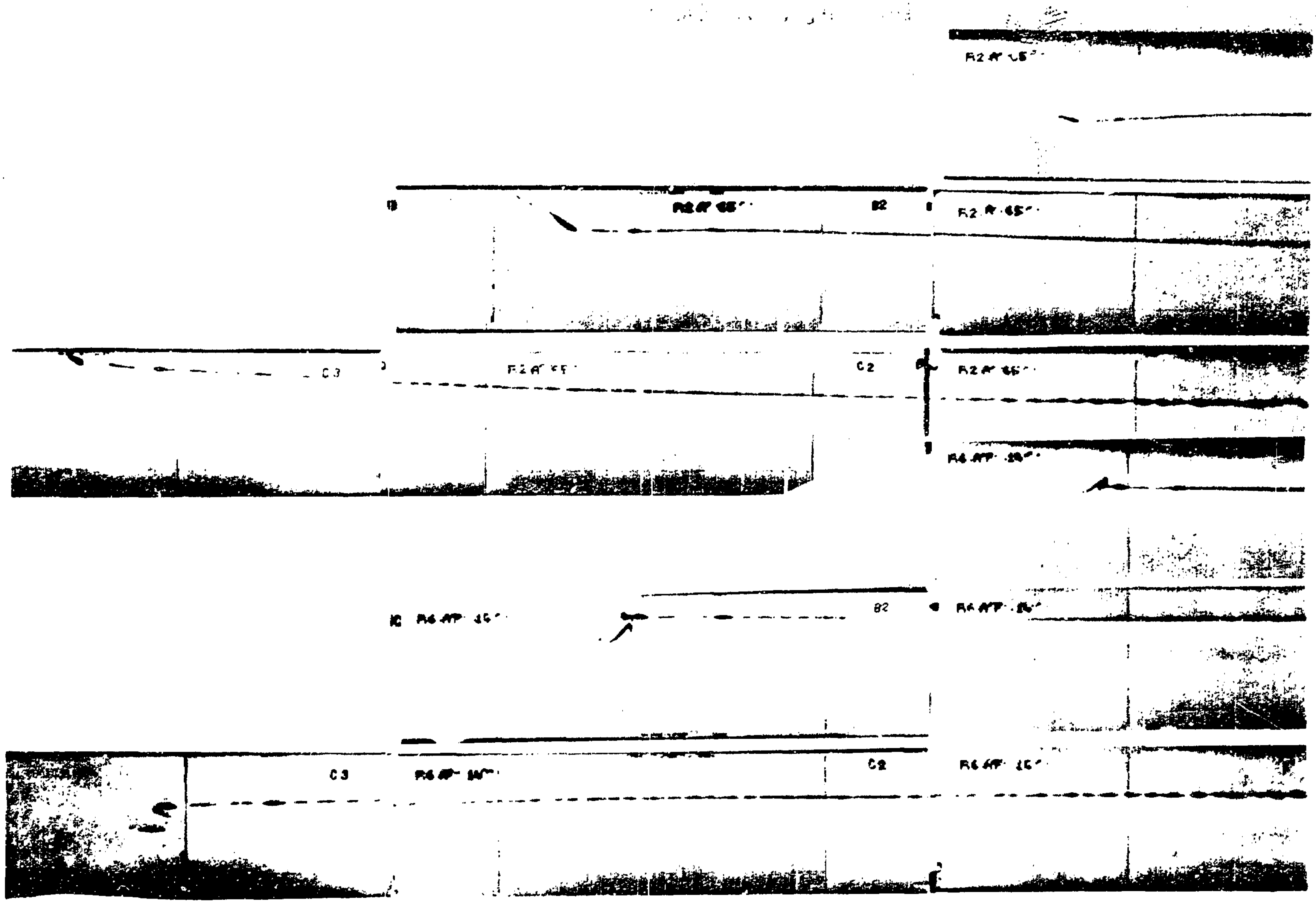


Figure 33. Triple-flash radiographs; top, A65 at 0 rps; lower, AF14 at 15 rps

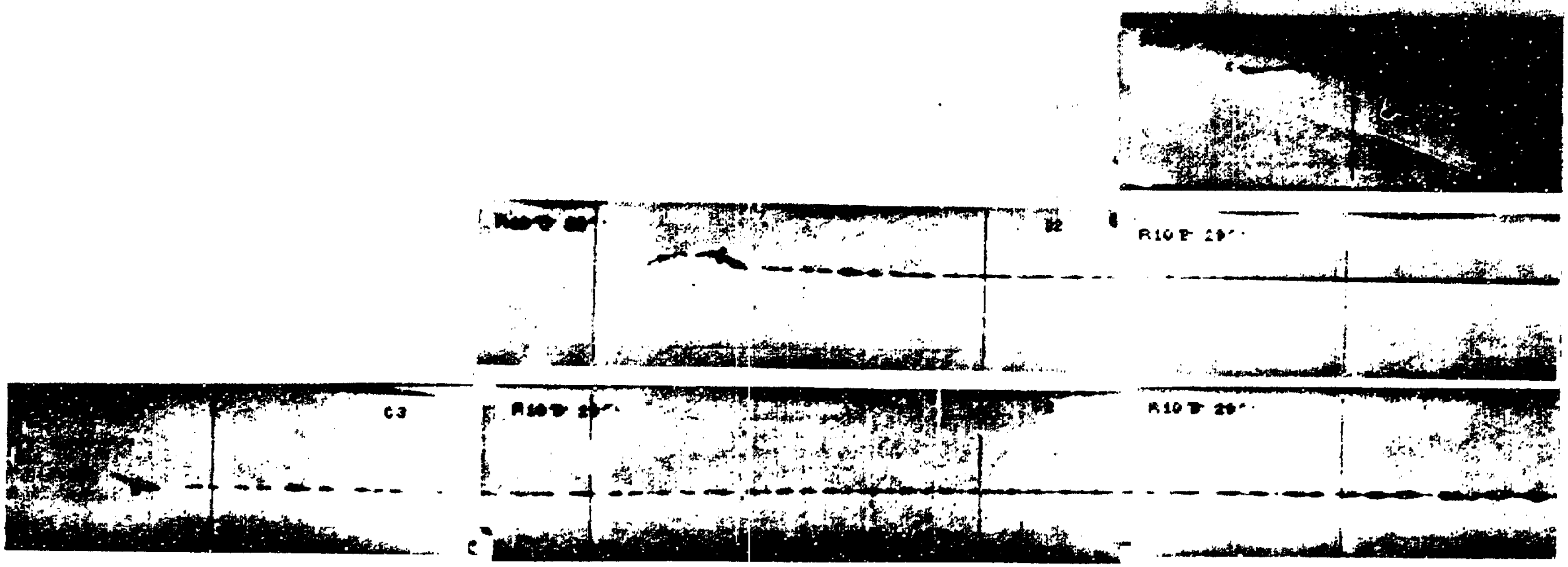


Figure 34. Triple-flash radiography, liner B20 at 15 rps

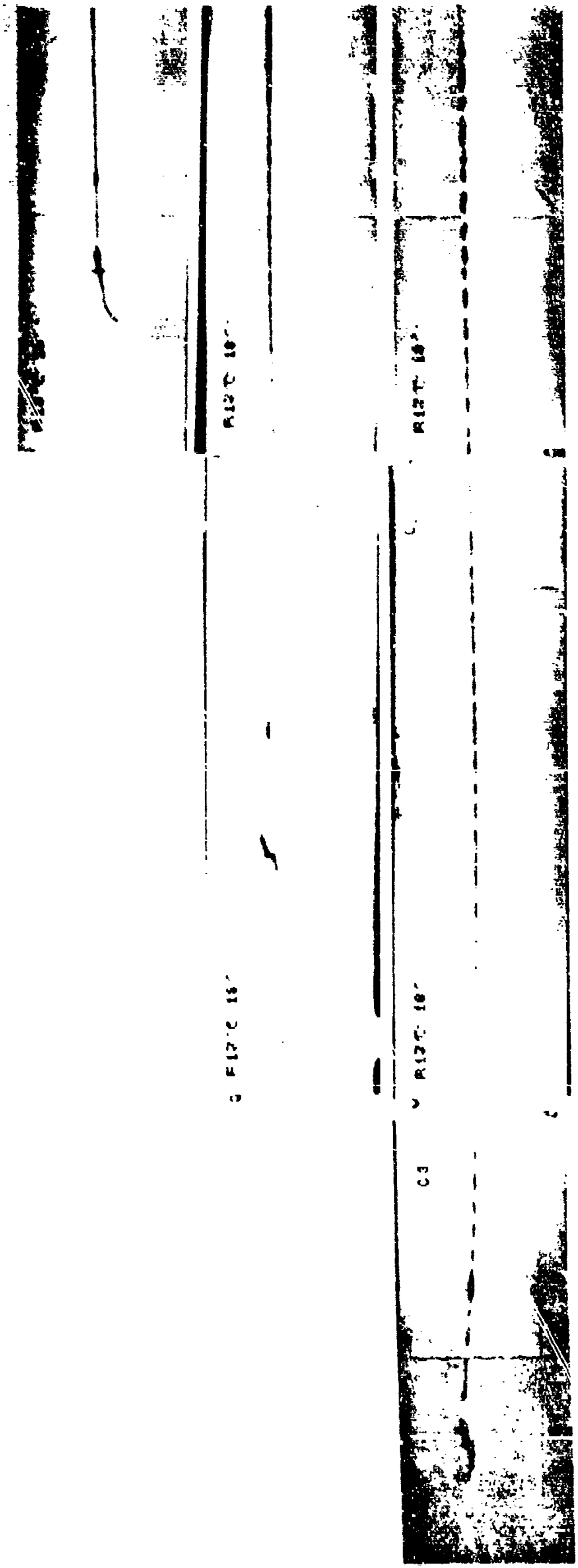


Figure 35. Triple-flash radiograph, liner C18 at 15 rps

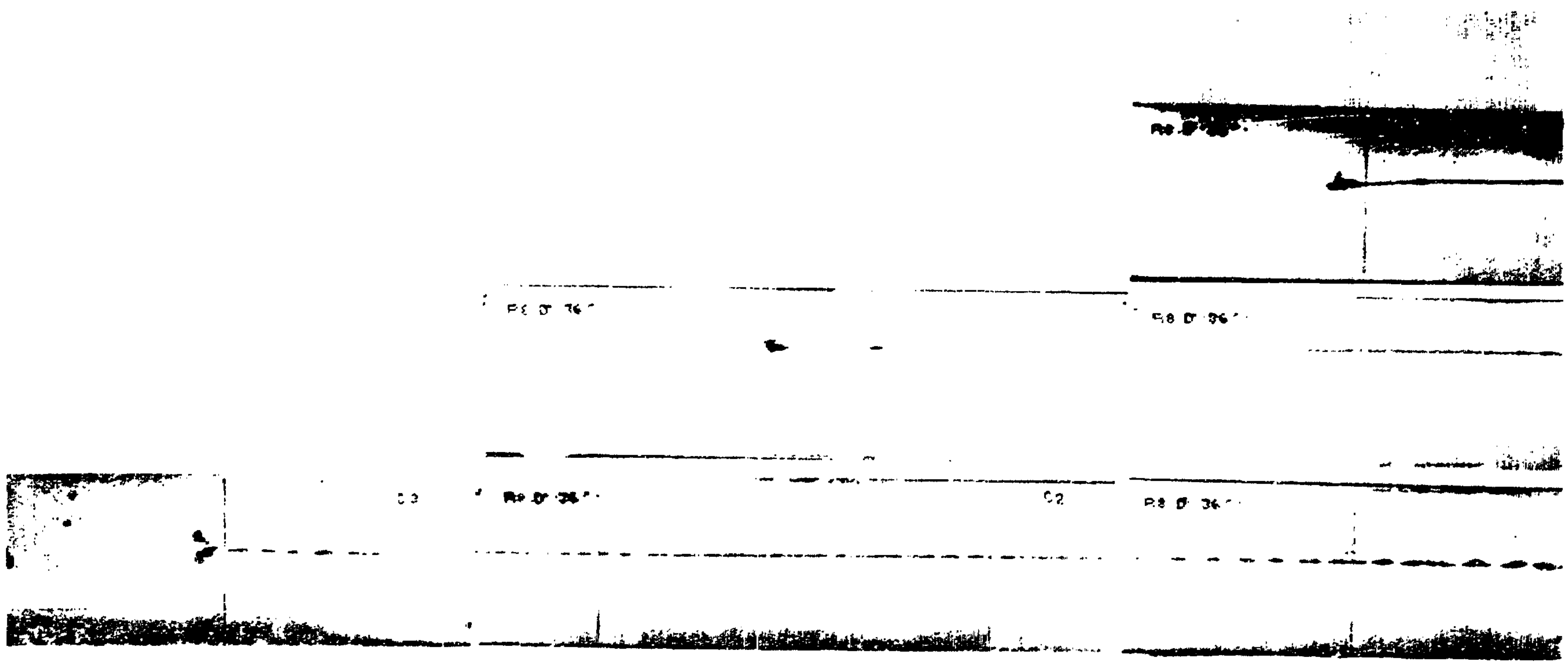


Figure 36. Triple flash radiograph, liner D36 at 15 rps

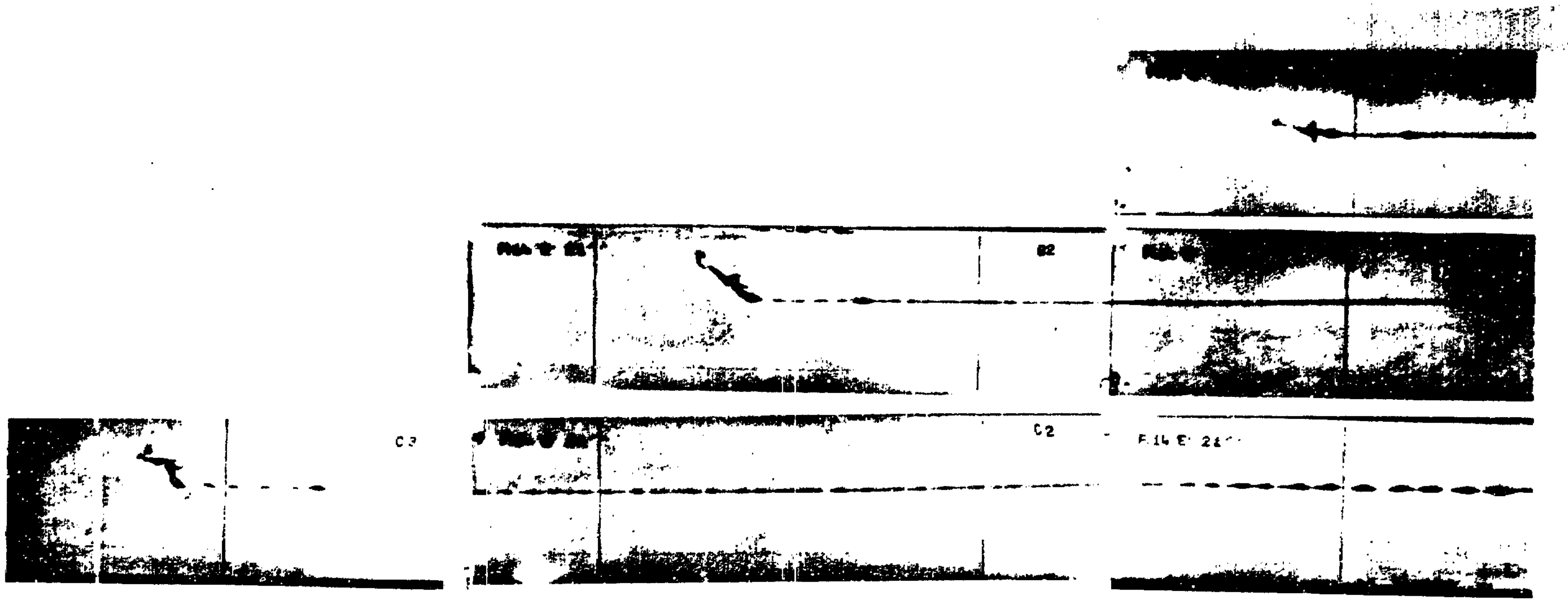


Figure 37. Triple-flash radiograph, liner E21 at 15 rps

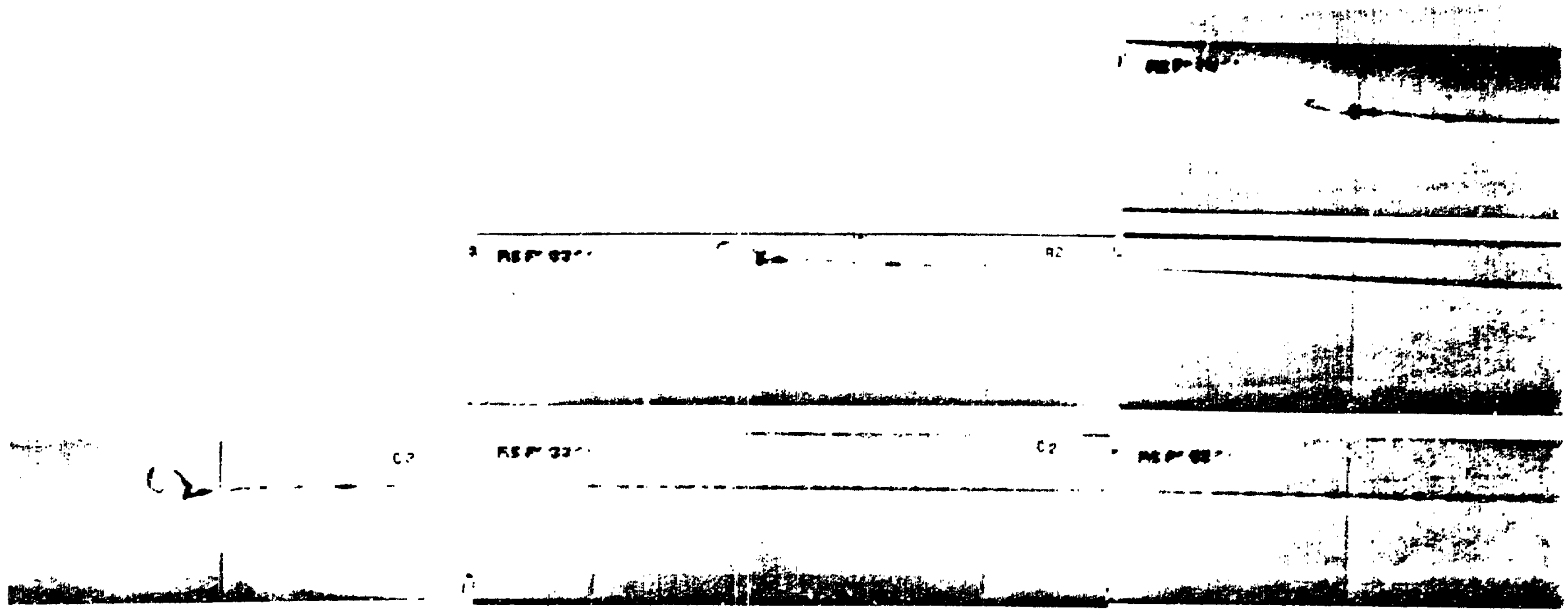


Figure 38. Triple-flash radiograph, liner F33 at 15 rps

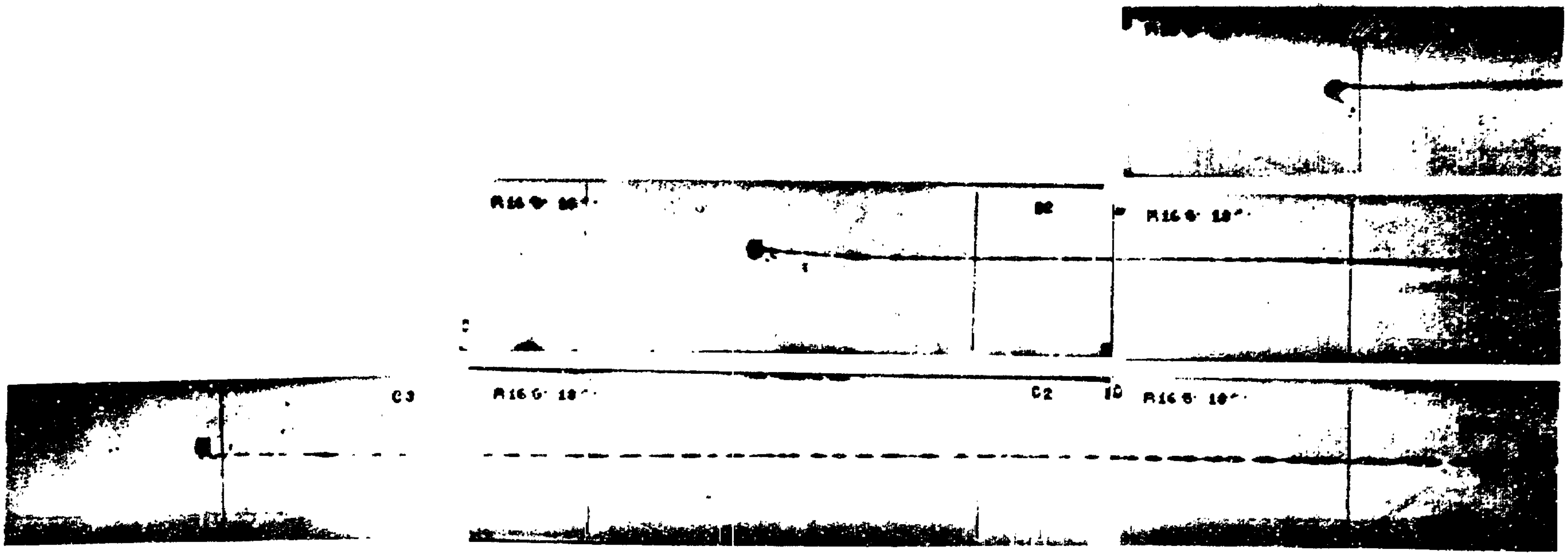


Figure 39. Triple-flash radiograph, liner G18 at 15 rps

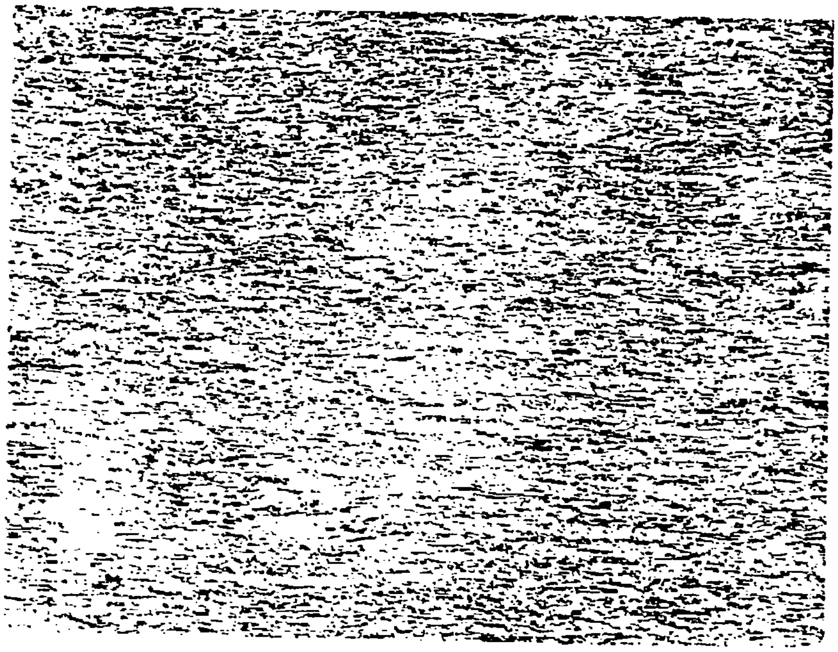


Figure 40. Uniformly wrought condition of typical as-spun liner

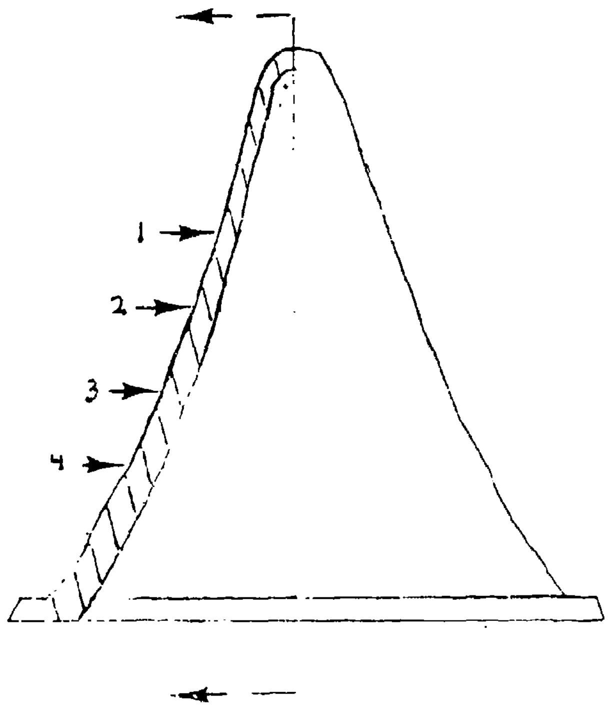


Figure 41. Location of liner hardness measurements

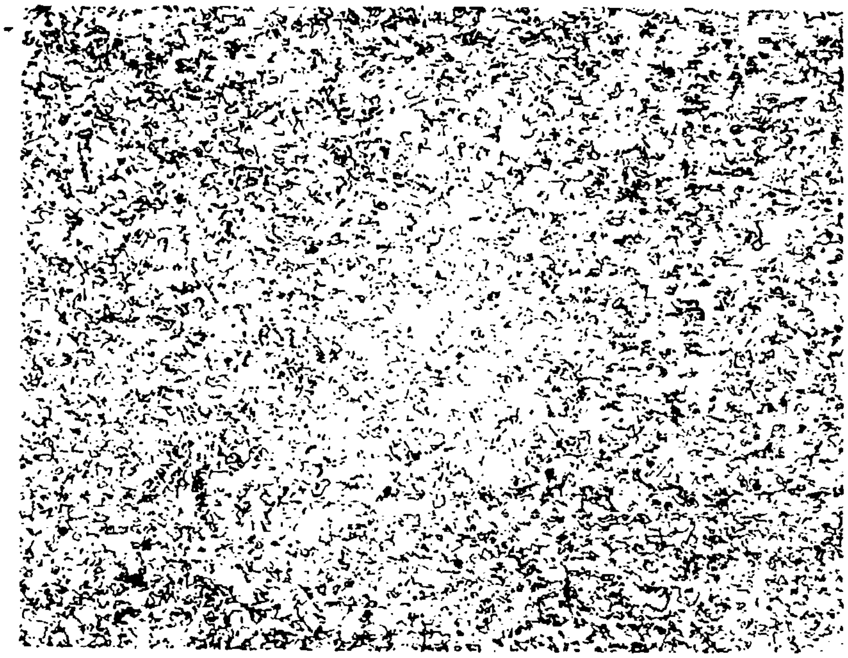
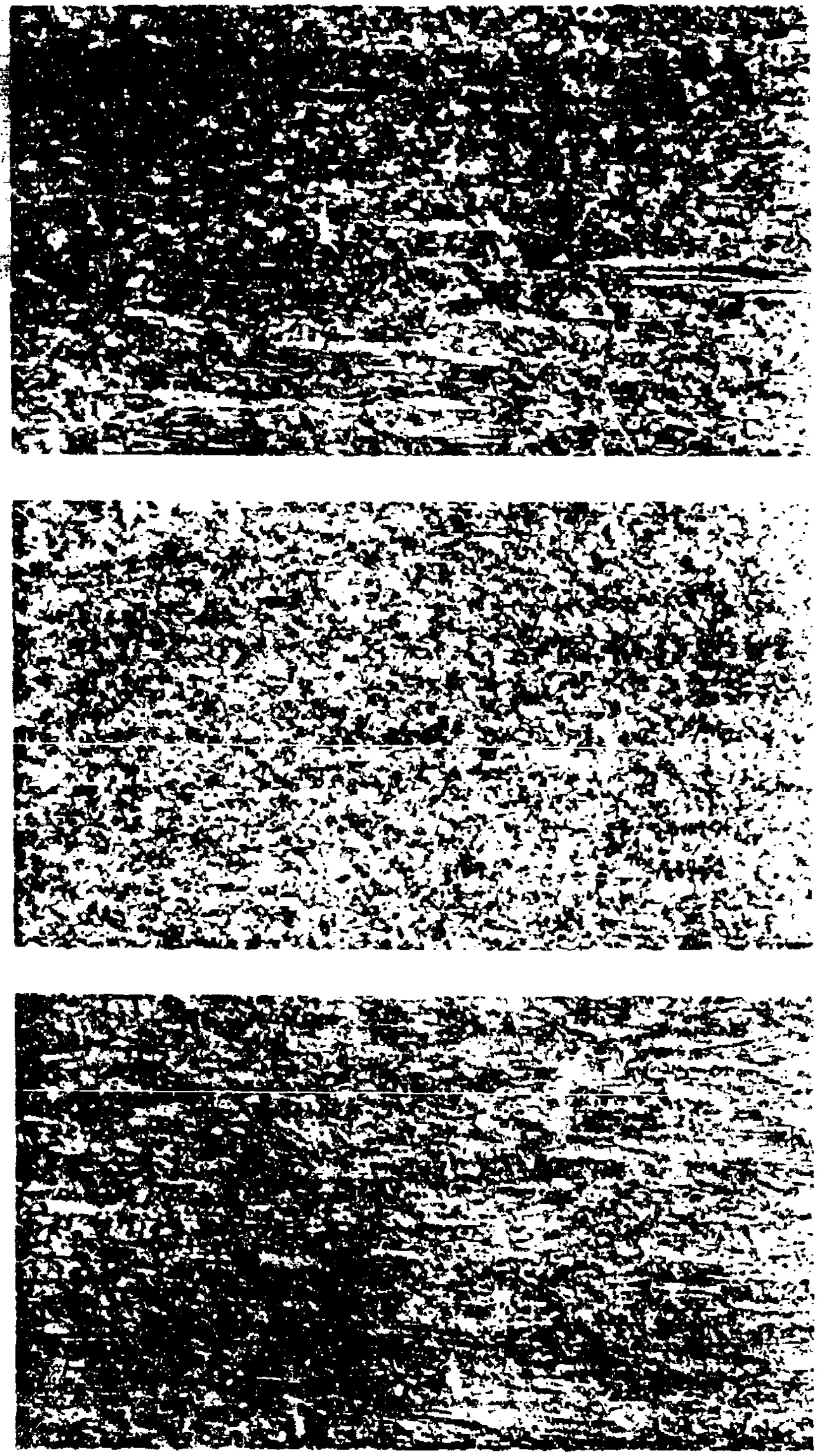


Figure 42. Recrystallized 15 micron grain size typical of group A through F annealed liners



Near apex

Midlength

Near flange

Figure 43. Group G annealed liner

APPENDIX

DETAILS OF THE OCTOL LOADING OF THE 105 mm HEAT-T M456 PROJECTILES

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Heavy Armament Division, Close Combat Armaments Center evaluated shaped charge liners using 75-25 octol loaded M456 105 mm HEAT-T projectiles as the test vehicles. Milan Army Ammunition Plant (MAAP) was tasked with loading these projectiles. After MAAP failed at several attempts to load the projectiles, the Heavy Armaments Division requested assistance from Energetics Systems Process Division (ESPD), Armaments Engineering Directorate (AED). A loading test plan was generated by ESPD. The results of the loading tests are described below. The loading efforts were accomplished on the X-41 line which is normally used for Comp B loading of the M456 projectile.

The problems experienced by MAAP in attempting to octol load the M456 projectiles included large 360-degree cavities in the C section, small cavities in sections A and B, porosity and annular rings. Sections A, B, and C are defined by figure A1. MAAP attributed these failures to octol with bad loading characteristics. The octol came from lot HOL-80-001-656. Limited funding and metal parts and repetition of loading tests without beneficial results influenced Heavy Armaments Div to order a new lot of octol (lot HOL-80-001-664) and assistance from ESPD. ESPD assessed the test data and determined that the most likely cause of the defects was typical of improper metal parts preheat and controlled cooling process. They generated a loading test plan which solved the cast loading problems.

Initial efforts were spent by ARDEC representatives in going over equipment setup requirements and process parameters. Particular attention was paid to getting the controlled cooling tunnel up to the required temperature of $140 \pm 5^{\circ}$F. This was done by enclosing the top of the controlled cooling tunnel and by turning on the internal steam panels and one half inch steamlines. In processing Comp B loaded M456 projectiles, MAAP normally leaves the tunnel top open and steam panels off. The tunnel was preheated from midmorning until pour time of 5:00 PM. Throughout the preheat period, the tunnel temperature was monitored for compliance with the requirements.

Besides proper operation of the equipment, preheating the M456 105 mm projectile bodies was a major concern since line X-41 had no on-line oven. The problem was solved by preheating the parts in an oven on line X-12 and transporting them to line X-41 in a wooden box lined with styrofoam insulation. The methods of preheat and transport were deemed acceptable. These conditions were used in loading the initial test run of 9 samples and the required quantity of 163 projectiles.

X-ray analysis of the 9 test run samples of the M456 105-mm projectiles, loaded with octol, were defect free. This formed the basis for loading the required quantity of 163 projectiles. X-ray analysis of the 163 projectiles revealed 99% acceptance (161 acceptable versus 2 rejects). Details of the test conditions are listed as follows:

Process Conditions

1. Loading and controlled cooling bays temperature, 96°F

2. Projectile preheat temperature at time of loading, 158 to 165°F (note 1)

3. Funnel preheat temperature, 155°F (note 2)

4. Projectile carrier rack temperature, 155°F (note 3)

5. Explosive pour:

   a. Explosive temperature, 191°F

   b. Kettle agitator speed (rpm), 37 (continuous)

   c. Pouring time, seconds

      (1) 5 seconds to within 2 inches from top of funnel with nozzle 1
      (2) 15 sconds to complete the fill to within 1/2-inch maximum from funnel top with nozzle 2

   d. Pouring nozzle size (inches), 1/2

   e. Vibration, amount could not be measured; the vibrator which is electromagnetic was operated at maximum capacity, continuous vibration for approximately 60 seconds

   f. Loaded projectile transfer time into controlled cooling tunnel seconds max, 60

6. Controlled cooling:

   a. Tunnel temperature, 140 to 160°F at funnel height (note 4)

   b. Belt speed, approximately 6 1/2 in./min

   c. Projectile residence time in tunnel, 90 min (note 5)

   d. Cool down cycle:

      (1) temperature, 96°F
      (2) time, 5 hours minimum

7. Insulation under liner, prior to preheating the projectiles, the entire exposed surface of the underside of the liner was crammed with fiberglass insulation. A styrofoam disc was added to assure the fiberglass would remain in place.

NOTES:

1. a. The projectiles were preheated for 20 minutes in an oven set at 240°F. The oven was located on line X-12 at Milan AAP. The projectile temperatures upon removal from the oven ranged between 174 to 183°F. The average projectile temperature at the time of pour was 165°F.

b. The liner and body of each projectile were at the same temperature at the time of pour.

c. Upon removal from the preheat oven, the projectiles were transported from line X-12 to line X-41 in a styrofoam lined box. The trip took approximately 10 minutes.

2. The pouring funnels were preheated in a hot water bath to a temperature of 155°F. Upon removal of the funnels from the water bath they were wiped dry and checked for proper temperature.

3. The projectile carrier rack was preheated in a hot water bath to a temperature of 155°F. The heated rack helped to maintain the proper temperature in the liner area of projectile.

4. The temperature of the tunnel was achieved using 2 pairs of 1/2-in. steamlines and steam panels on either side of the tunnel where the pressure was 15 psig. The steamlines were in intimate contact with the necks of the projectiles to compensate for cast shrinkage. The tunnel had three temperature zones. The zone nearest the pouring machine was the hottest with the zone farthest away being the coolest. During the initial test pour with the 9-sample projectiles, the temperatures were 146, 142, and 138°F in zones 1, 2, and 3, respectively after the projectiles were introduced. Before the required quantity of 163 projectiles were introduced into the tunnel, the temperatures were 160, 160, and 142°F for zones 1, 2, and 3, respectively.

5. After the projectiles were loaded, the conveyor belt was turned off. This allowed a projectiles residence time of 90 minutes in a heated environment. This was done to keep the explosive in the funnel molten long enough to give a good product feed into the projectile bodies to compensate for cast shrinkage. After the 90-minute residence time was completed, the belt was turned on again with the steamlines still active. This resulted in approximately 20 minutes additional heat exposure.

Core samples of the expolsive casts were taken from two of the octol loaded projectiles shipped to ARDEC. The results of the chemical and density analyses of these core samples are shown in figures A2 and A3. In each case, the mean overall density is 1.78 g/cm^3 which is 98% of theoretical density. These analyses indicate good explosive casts. The quality that can be expected of projectiles loaded with octol using ESPD's loading plan is shown in figure A4.

Funding constraints precluded dedicated pushout tests for assessing cast tightness. Nevertheless, the casts were so tight against the projectile walls that they could not be pried out by normal means. To facilitate removal of the casts for coring and disposal, the projectiles had to be heated to melt the explosive surface.

The basic flow pattern for the process used for all loading efforts is shown in figure A5. Operations given on the flow chart are self descriptive.

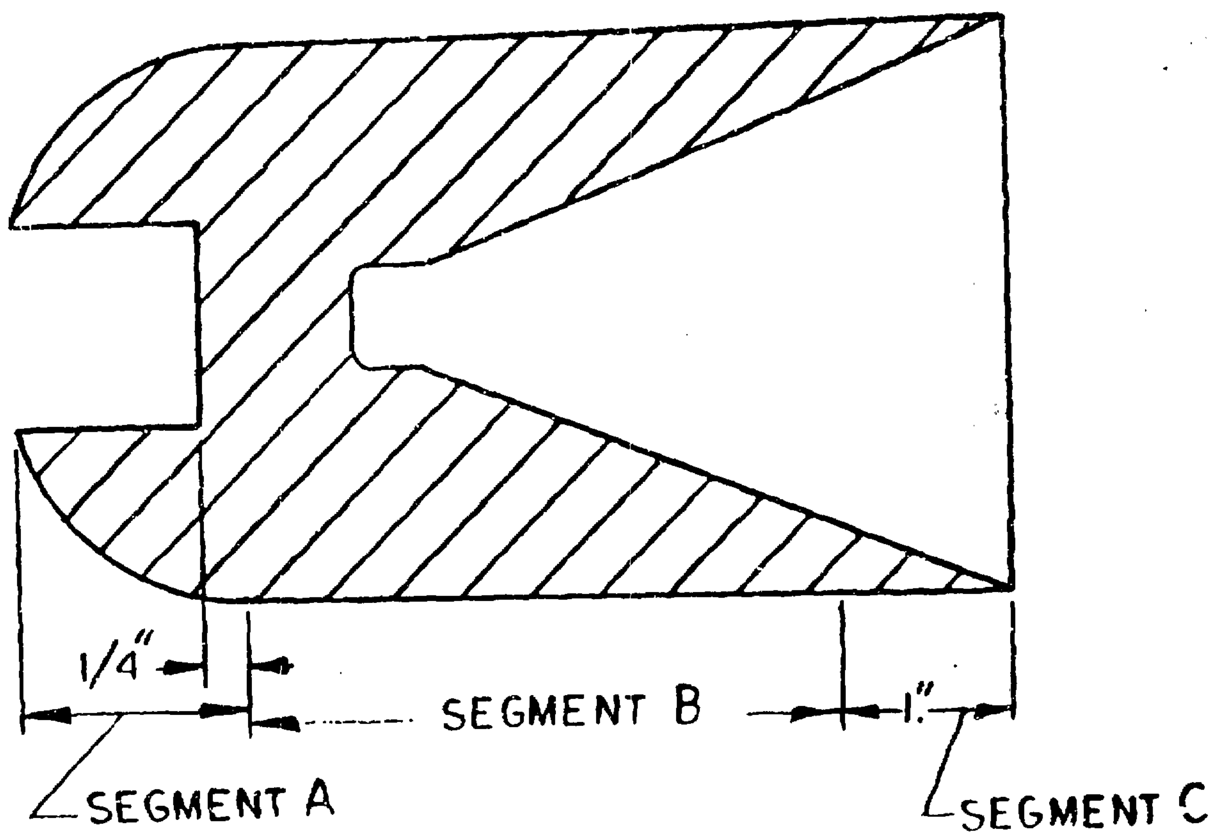

Figure A1. Sections A, B, and C of explosive fill

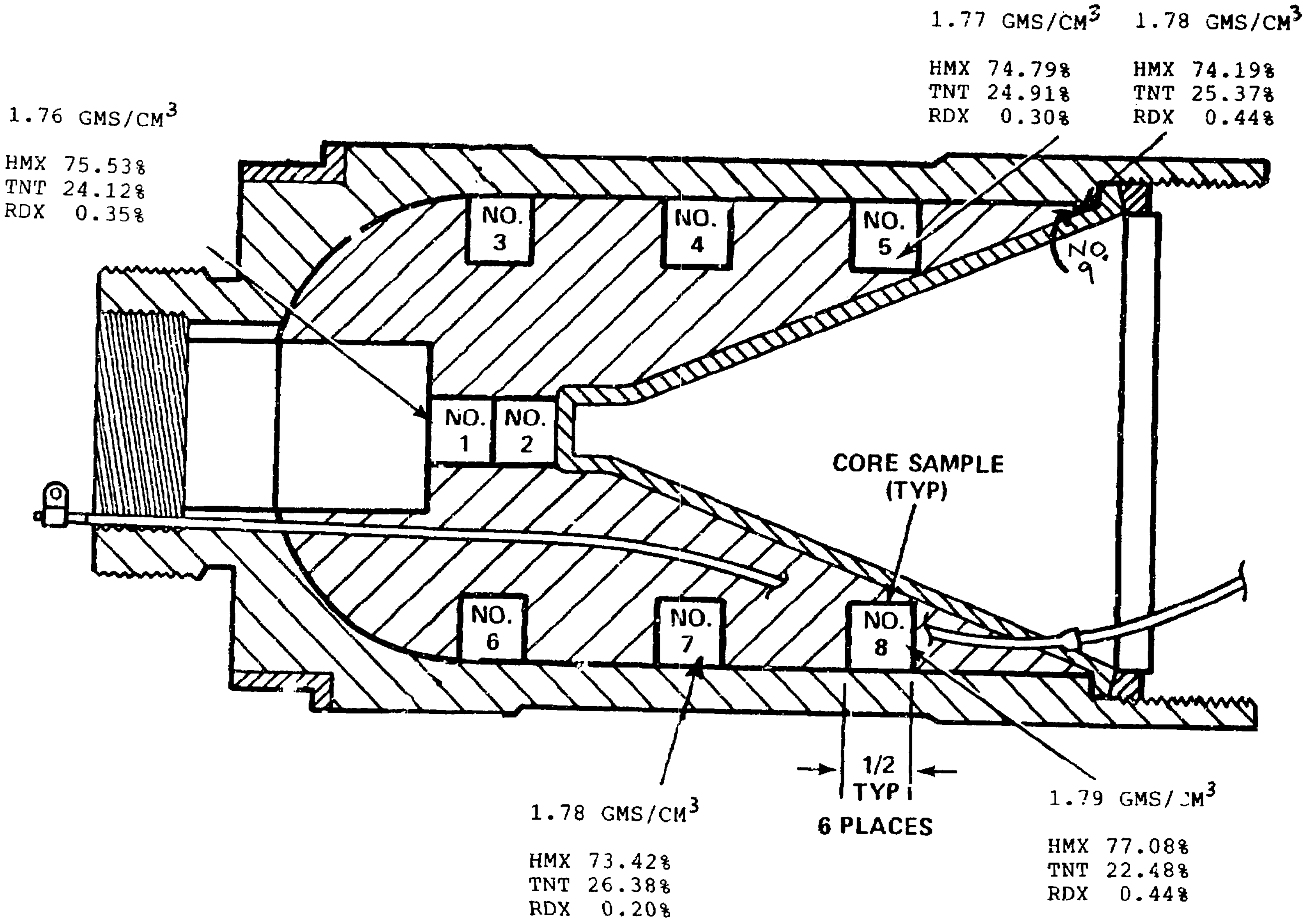

Figure A2. Octol explosive density and composition analysis

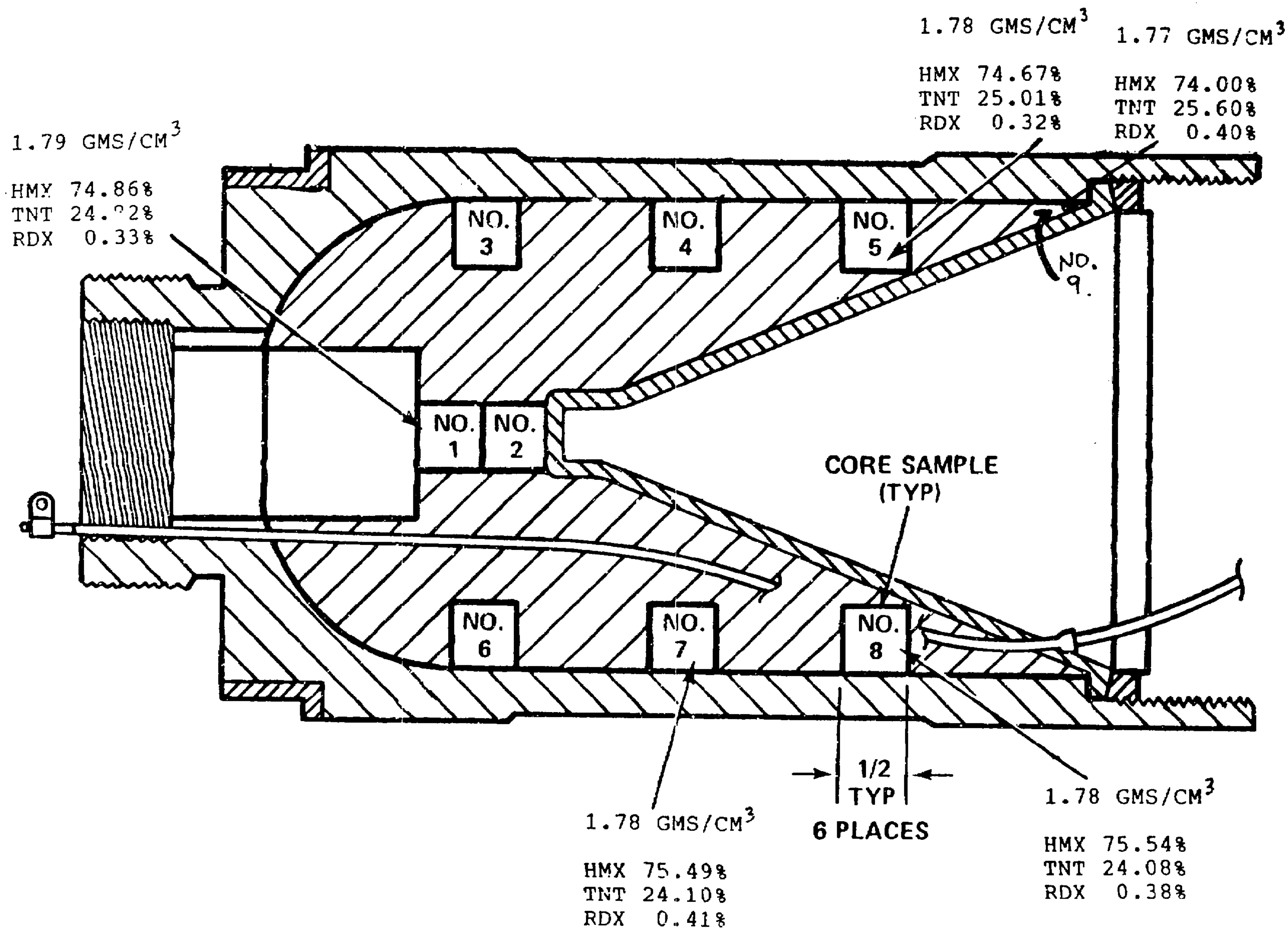

Figure A3. Octol explosive density and composition analysis

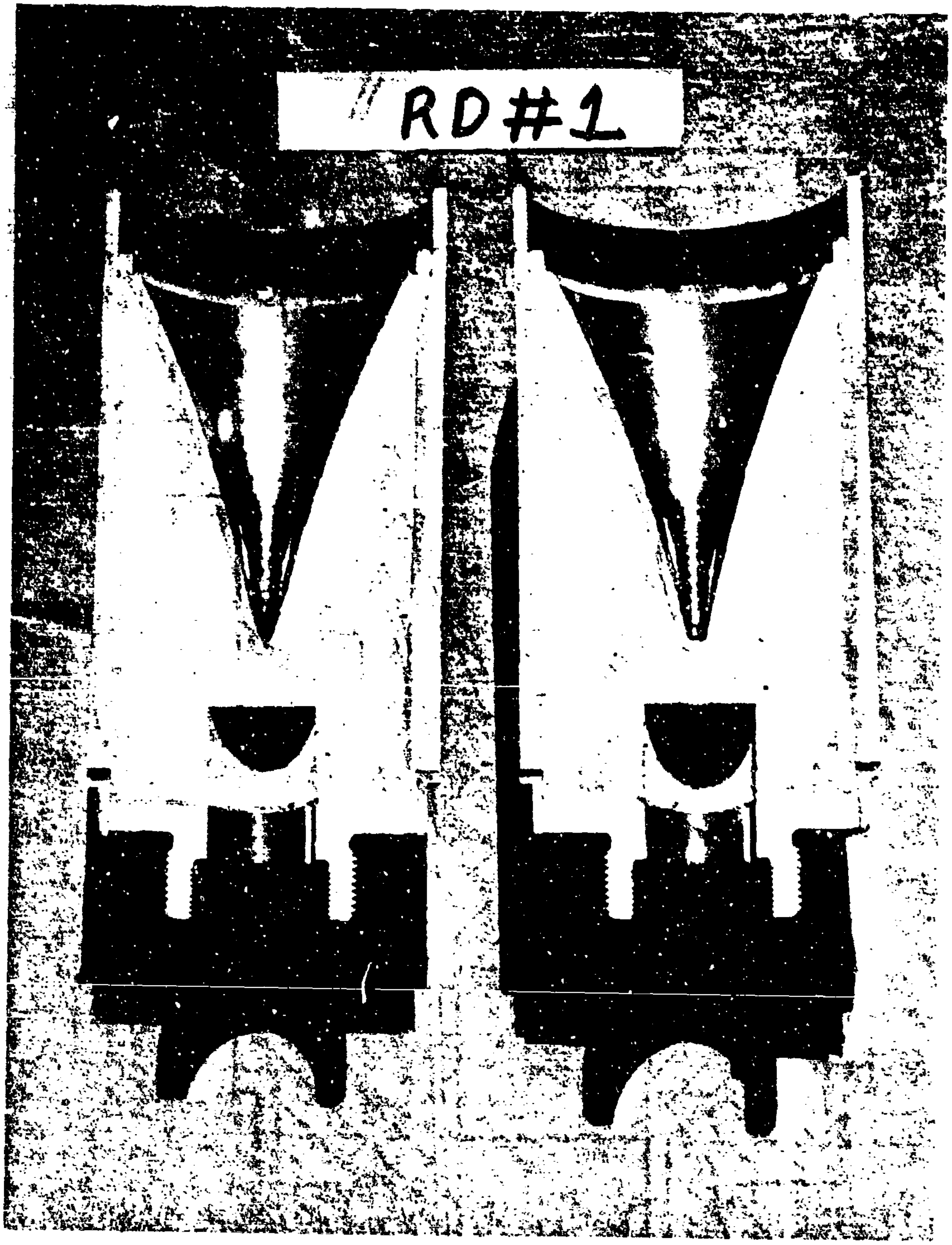

Figure A4. Sectioned loaded warhead

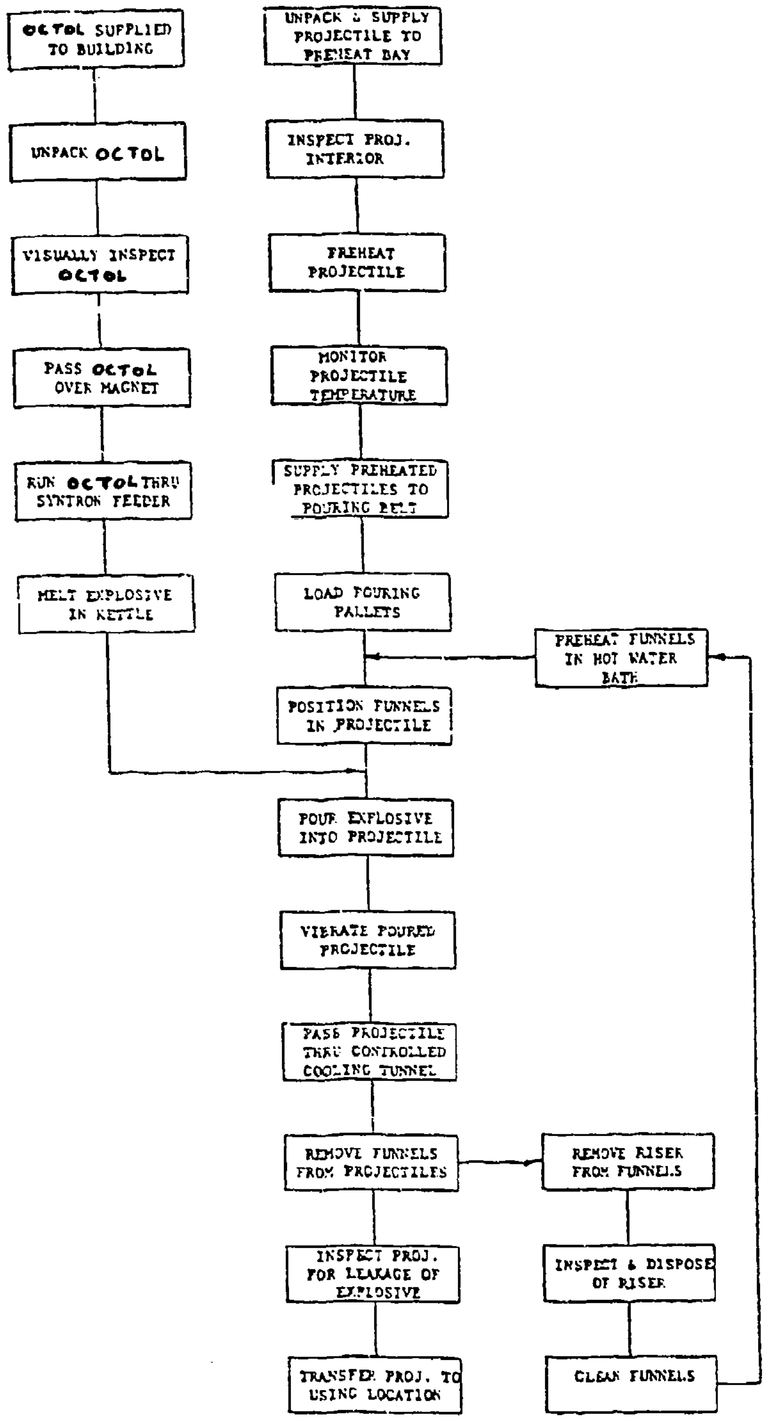

Figure A5. Flow chart for Octol explosive loading

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